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Evolution of ancient harbours in deltaic contexts: a geoarchaeological typology

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Abstract

In deltaic areas, within a context of relative sea-level stability during the past 6000 years, environmental conditions have been key in mediating human settlements and the evolution of ancient harbours. The natural diversity of clastic-coast environments, in particular deltas, is central to explaining the wide disparity in harbour contexts. It is, therefore, important to understand the impact of these settlements on the evolution of clastic coasts. How did ancient societies exploit and adapt to deltaic environments? Here, we detail a typology of ancient harbours on clastic coasts using a suite of multidisciplinary case studies from the Mediterranean and the Black Sea.

We present the impact of different forcing agents (floods, storms, sedimentary inputs, relative sea-level (RSL) changes, dredging and harbour structures) on the geomorphological evolution of selected harbour sites, and underline the important role of coastal changes at different temporal and spatial scales. These processes affected the infrastructure and the viability of harbours to varying degrees. In deltaic contexts, our analysis differentiates five harbour types: (1) fluvial harbours, affected by floods, rapid sedimentation and river-channel changes; (2a) infilled estuarine harbours; or (2b) submerged estuarine harbours, lying at the interface between marine and fluvial processes; (3) lagoonal harbours strongly affected by sedimentary inputs; and (4) the impact of humans on harbour basins via harbour protection structures and dredging. For these harbour types, we probe the advantages and disadvantages of each geomorphological setting, in addition to the consequences of environmental pressures on human societies.

Key words: delta; ancient harbour; sediment supply; lagoon; estuary; landscape archaeology; geoarchaeology; geomorphology; coasts; relative sea-level changes; Mediterranean; Black Sea; Holocene.

1. Introduction

The Holocene morphogenesis of Mediterranean deltas can be divided into two main successive steps (Anthony *et al.*, 2014). First, the glacio-eustatic stabilisation of sea level since ca. 6000 years, associated with continental sedimentary inputs, which favoured the widespread progradation of clastic coasts (Stanley and Warne, 1994, 1997; Hori *et al.,* 2004; Catuneanu and Zecchin, 2006; Anthony *et al.*, 2014). Subsequently, the importance of human impacts, mainly linked to watershed deforestation, which led to soil erosion and an increase in fluvial sediment supply that accentuated the expansion of deltaic lobes until the mid-20th century (e.g. Bellotti *et al.*, 2007; Simeoni and Corbau, 2009; Maselli and Trincardi, 2013).

Deltaic environments, which constitute depocenters for fluvial sediments, have been occupied by human societies since the stabilisation of sea level during the mid-Holocene acting, in many instances, as cradles for the emergence of early social complexity (Stanley and Warne, 1997; Day *et al.*, 2007; Kennett and Kennett, 2006). In the Western Mediterranean, human influence has been highlighted in the formation of several Italian deltas. Marchetti (2002) proposed that human impacts have been decisive in modulating the evolution of the Po River since Roman times due to the intensive exploitation of its catchment between the 1st and the 3rd centuries AD. More locally, the deltas of the rivers Arno and Ombrone manifest a similar evolution and chronology. Their morphogenesis is mostly attributed to the past 2500 years, following the massive deforestation of their catchments (Pranzini, 2001, 2007; Bellotti *et al.*, 2004; Amorosi *et al.*, 2013). This contemporaneous evolution of deltas during the last 2500 years has led to the term "man-made deltas" being coined (Maselli and Trincardi, 2013).

Progradation led to important changes in coastal landscapes and had a direct impact on littoral societies leading, in many well-documented cases, to the deterioration of harbour accessibility and functioning (see **Figure 1** for the location of the sites mentioned in this paper). In Asia Minor, Miletus' and Ephesus' ancient harbours, located in ria-type deltaic environments are now located several tens of kilometres inland and underwent important environmental changes over time (Brückner *et al.*, 2017). These ria-type deltas evolved following a three-phase model (Anthony *et al.*, 2014). At Ephesus, Brückner (2005), Stock *et al.* (2013, 2014, 2016) and Brückner *et al.* (2016), have shown that these three phases comprised: (i) the flooding of a tectonic graben by postglacial sea-level rise, creating a fluvial embayment around 8000 to 6000 years ago. Such environments were particularly conducive to human settlement because they lay in a sheltered position compared to the open coast and they had direct access to freshwater due to the proximity of the river. (ii) The rapid westward progradation of the deltaic front of the

Küçük Menderes since 6000-5000 years BP, much like the nearby ria of the Büyük Menderes, illustrates the first environmental pressures that can affect harbours (Brückner *et al.*, 2014, 2016); and (iii) a straightening of the shoreline at the ria mouth, engendering a landlocking of the harbours on the deltaic plain. In the same vein, geoarchaeological research on the Acheloos delta in Greece (Epirus) has highlighted the effects of deltaic progradation on shoreline changes and harbour landlocking (Vött, 2007; Vött *et al.*, 2007; **Figure 2**). The palaeo-island of Trikardo, which accommodated the city of Oiniadai, was washed by the sea 6000 years ago because of sea-level rise. Thereafter, the progradation of the Acheloos River delta isolated the island from the sea. The ancient harbours remained connected to the sea via fluvial arms, which acted as communication channels. By Roman and Byzantine times, the island was permanently landlocked and integrated into the deltaic plain. This limitation was overcome by the establishment of a fluvial harbour, on the bank of a meander of the Acheloos, on the southern part of the island. This relocation of the harbour is typical of the "race to the sea" induced by the environmental changes at that time.

Deltaic environments show specific geomorphological and ecological particularities, and offered numerous natural potentialities for human societies and harbour activities during Antiquity. The objective of this paper is to demonstrate that environmental changes have played a major role in the geomorphological evolution of ancient harbours in deltaic contexts since the Bronze Age. We also shed light on the potentialities that deltaic environments offered for societies and commercial activities, as well as the role of human impacts in shaping the evolution of harbours. For this purpose, we use case-study examples to probe the impacts of the diverse environmental pressures on the evolution of deltaic harbours. We highlight the (dis)advantages of each geomorphological context identified.

2. Defining a typology

The diversity of deltaic environments is illustrated by the wide plethora of geomorphological contexts in which harbours were located. It is interesting to define a geoarchaeological typology that translates the geomorphological trajectory of ancient deltaic harbours over time. The typology includes the influence of rivers, marine processes and human societies. We identified several pressures that affect harbours with respect to their geomorphological context (mainly their location in relation to the river channel/mouth or to the sea).

2.1. Identification of the forcing agents

We detail different environmental pressures and human impacts.

Because deltas are depocenters for sediments eroded from the watershed, one key environmental variable affecting harbours over time is fluvial sediment supply. Over the last 6000 years, Mediterranean clastic coasts have undergone an important progradation at all spatial scales, after the deceleration of sea-level rise and an increase in fluvial sediment supply to base-level depocenters (Stanley and Warne, 1994; Stewart and Morhange, 2009; Syvitski and Kettner, 2011; Maselli and Trincardi, 2013; Anthony *et al.*, 2014). These factors explain why ancient populations had to constantly adapt to coastal progradation and landscape change. In Cyprus, Devillers (2008) demonstrated that the Gialias ria was flooded by the sea 8000 years ago, following the post-glacial sea-level rise. He elucidated a succession of coastal palaeoenvironments (alluvial plains, lagoons, coastal spits) consistent with the eastward migration of the coastline during the past 6000 years. Since the Bronze Age, local populations have had to adapt to these environmental changes and relocate their harbours to keep pace with the shifting coastline. In Medieval times, this “race to the sea” led to the relocation of the harbour at Famagusta, on the waterfront outside of the infilled ria (**Figure 3**).

At Utica the importance of deltaic progradation in shaping harbour location and activities has been highlighted (Mejerda delta, Tunisia; Chelbi et al., 1995; Delile *et al.*, 2015). Progradation of the Mejerda delta from the south-west led to the development of a first deltaic lobe along the southern part of the promontory that had already started prograding at the time of the foundation of the Phoenician city (12th century BC), which hindered the development of maritime activities. The harbour had to be located north of the promontory and was linked to the sea via a maritime corridor west of the northern part of the delta (Chelbi *et al.*, 1995; Delile *et al.*, 2015).

Deltas are land-sea interfaces. We have identified two pressures linked to high-energy events. The first relates to river floods and the second to meteo-marine events affecting the coast. River floods can cause important destruction as attested at Pisa, where excavations in the harbour basin have led to the discovery of 16 ancient boats destroyed during flood events (Benvenutti *et al.*, 2006; Allinne *et al.*, 2016). At Narbonne (Sanchez *et al.*, 2014, in press; Faïsse *et al.*, 2018), repairs to the embankments of the artificialized channel of the Aude River were frequent during the Early Roman Empire and reveal the challenges of maintaining the river in its bed. These high-energy events raise the question of the impact of floods on the organisation of urban areas and ancient harbours, particularly in fluvial contexts (Arnaud-Fassetta *et al.*, 2003;

Benvenutti *et al*., 2006; Allinne, 2007; Arnaud-Fassetta *et al*., 2010; Leveau, 2012; Ruiz *et al*., 2014; Bini *et al*., 2015; Allinne *et al*., 2016; Salomon *et al.,* 2017).

Meteo-marine dynamics and high-energy events are well documented on clastic coastlines (Marriner *et al*., 2017). In the Northern Adriatic Sea, Kaniewski *et al*. (2016) highlighted six different storm phases during the last 4500 years on the Mirna Delta (Croatia). These storm phases affected coastal agriculture and were correlated with periods of low solar activity, corroborating previous work by Camuffo *et al*. (2000). The impacts of storms are limited for naturally protected deltaic harbours (river mouths, lagoons), except in the case of exceptionally intense events, in contrast to open sea harbours located along the waterfront. Nonetheless, we would like to insist upon the fact that such evidence is difficult to observe in the sedimentary record. For instance, the sedimentological traits of storm facies are extremely challenging to differentiate from those generated by tsunamis (Dawson and Stewart, 2007; Morton *et al*., 2007; Engel and Brückner, 2011; Engel and May, 2012; Goff *et al*., 2012; Weiss, 2012; Pilarczyk *et al*., 2014; Marriner *et al*., 2017).

The fourth forcing agent identified is related to RSL changes. During the Holocene, sea-level changes in tectonically stable regions are primarily linked to modifications in ice volumes and the Earth's response to the changing ice-water load. During the last 4000 years, the ice-equivalent melt-water input is considered minimal and does not exceed 1m (Lambeck *et al*., 2004, 2009; Vacchi *et al*., 2016, 2018). In deltaic settings, the compaction of unconsolidated fine-grained sediments can lead to important RSL rise (Stanley, 1997; Törnqvist *et al*., 2008; Teatini *et al*., 2011; Marriner *et al*., 2012). In southern Italy, the Crati Delta, where the ancient Greek cities of Sybaris, Thuri and Copia are located, was affected by rapid progradation and long-term subsidence (Pagliarulo, 2006; Stanley and Bernasconi, 2009, 2012). Tectonic activity can also play a role in RSL changes at short timescales. This variable, which can lead to important modifications in the shoreline and sometimes to the isolation of the port from the open sea, is nonetheless restricted to a small number of harbours, particularly in the central and eastern Mediterranean (Stewart and Morhange, 2009).

We identified human-related pressures highlighted by the variable density of harbour works. These reflect the evolution of harbour building techniques during Antiquity, and shed light on the importance of harbour dredging. Furthermore, at a wider geographic scale, human impacts played a key role in the intense deforestation of watersheds (Quézel and Médail, 2003) that, in conjunction with external dynamics (tectonics, climate variability) can lead to increases in fluvial sediment supply to coastal systems at base level (Dearing and Jones, 2003; Casana, 2008;

Syvitski and Kettner, 2011; Dusar *et al.*, 2011) and therefore the infilling of harbours.

Early coastal societies sought to reinforce natural coastal endowments in order to install permanent harbour areas (Blackman, 1982a, 1982b; Marriner *et al.*, 2014, 2017b; Morhange *et al.*, 2016b). The earliest evidence for artificial harbour works is dated to the Bronze Age and derives from the Red Sea. Archaeological surveys at Wadi al-Jafr (Egypt) have highlighted the presence of a large artificial anchorage, covering around 2.5 hectares (0.02 km^2), framed by an L-shaped mole dating to the Fourth Dynasty (2613-2494 BC; Tallet and Marouard, 2014, 2017). On clastic coasts, inhabitants favoured naturally-protected areas. But they could also manually dig basins, as was the case for Lechaion which was excavated out of a marsh area during the 6th century BC, at the mouth of a coastal stream (Stiros *et al.*, 1996; Morhange *et al.*, 2012; Kolaiti *et al.*, 2017). In Roman times (1st-2nd centuries BC), an intensification of harbour building, resulting from the discovery of hydraulic mortar (Pozzolana), allowed artificial basins to be erected on the seafront (Brandon *et al.*, 2014). Several examples are known in the Mediterranean, such as Frejus (Gébara and Morhange, 2011) or *Portus*, with the construction of Claudius and Trajan basins (Keay *et al.*, 2005; Goiran *et al.*, 2010). The dredging of harbours is another example of human activities affecting harbour environments (Marriner and Morhange, 2006; Morhange and Marriner, 2010). The most iconic example comes from the ancient harbour of Neapolis (Naples). The harbour bottom was completely reshaped by intensive dredging between the 4th and the 2nd centuries BC, leading to the absence of older sediments in the basin (Giampaola *et al.*, 2004; Carsana *et al.*, 2009; Di Donato *et al.*, 2018; **Figure 4**). The power of the dredging technology used is attested by the dimensions of the fossilised dredging scars, 80–165 cm wide and 30–50 cm deep. Such operations are recorded until the abandonment of the harbour in the 5th century AD (Di Donato *et al.*, 2018).

2.2. Estimating the weight of forcing agents

We built a semi-quantitative database in which a percentage score was attributed to each forcing agent based on the scientific literature available for each site (see supplementary material for references). In Table 1, we detail the percentage values ascribed to the Bronze Age harbour of Tel Akko (Israel), to the Roman harbour of Ephesus (Turkey) and to the Eastern Harbour (Magnus Portus) of Alexandria (Egypt).

Table 1: Semi-quantified pressures for three harbours examples, Tel Akko (Israel), Ephesus (Turkey) and Magnus Portus of Alexandria (Egypt). The examples present three different harbours located in diverse geomorphological settings and for which the weight of each pressure

is different. The different estimates for all the sites included in the present study are described in the Supplementary Material.

Harbour	Period of use	Flood impacts	Sedimentary inputs	Storm impacts	Relative sea-level changes	Dredging	Infrastructure
Tel Akko Bronze and Iron Ages	2000 BC - 587 BC	**Low**	**High**	**Low**	**Absent**	**Absent**	**Absent**
		Possible low-energy floods	Infilling of the estuary attested	Marine-dominated estuary moderately exposed to the sea	Stable sea level since 4000 years	No direct evidence	No archaeological excavations
		Ø	Morhange *et al.*, 2016; Giaime *et al.*, 2018a	Morhange *et al.*, 2016; Giaime *et al.*, 2018a	Sivan et al., 2001	Ø	Ø
	Weight	2	3	2	0	0	0
	Percentage	28.5%	43%	28.5%	0%	0%	0%

Harbour	Period of use	Flood impacts	Sedimentary inputs	Storm impacts	Relative sea-level changes	Dredging	Infrastructure
Ephesus	1st c. BC – 7th century AD	**High**	**High**	**Possible**	**Possible**	**High**	**High**
		River channel diverted under Hadrian (129 AD)	Rapid progradation of the delta front	Limited exposure to the open sea	Linked to global sea-level changes	Dredging of the harbour and excavation of the channel	Excavation of an artificial basin and channel
		Kraft *et al.*, 2011; Stock *et al.*, 2013, 2016	Stock et al., 2016	Ø	Ø	Stock et al., 2013, 2016	Kraft *et al.*, 2011
	Weight	4	4	1	1	4	4
	Percentage	22%	22%	6%	6%	22%	22%

Harbour	Period of use	Flood impacts	Sedimentary inputs	Storm impacts	Relative sea-level changes	Dredging	Infrastructure
Alexandria -Eastern harbour (Magnus Portus)	4th century BC – 7-8th centuries AD	**Absent**	**Moderate**	**Low**	**High**	**Possible**	**Moderate**
		Ø	Infilling of the harbours and presence of a submarine tombolo	High-energy event in the harbour but protected basin (presence of fine-grained sediments)	Subsidence of the delta front due to the compaction of unconsolidated sediments	No direct evidence	Submerged ancient structures in the Eastern harbour
		Ø	Goiran *et al.*, 2005; Marriner *et al.*, 2008	Goiran *et al.*, 2012	Stanley *et al.*, 2006	Ø	Goddio and Yoyotte, 2008; Goddio and Masson-Berghoff, 2016
	Weight	0	3	2	4	1	3
	Percentage	0%	23%	15%	31%	8%	23%

2.3. Statistical analyses

Based on these estimates, we created a heat map to visually represent the data (**Figure 5**). The semi-quantitative database was analysed using hierarchical clustering and Principal Components Analysis (PCA). We chose to apply multivariate statistical techniques because they facilitate the investigation of large and complex datasets, while taking into consideration the effects of all variables on the responses. In this study, cluster analysis (Algorithm: Paired group; Similarity measure: Correlation) was used to group data according to the estimated importance of each pressure identified on the harbour (**Figure 5**). Subsequently, a PCA allowed us to test the ordination of the harbours according to the different pressures (**Figure 6**).

The cluster analysis and the PCA highlight four different groups (noted A to D), based on the weight of the pressures affecting them (**Figures 5 and 6**). In the PCA (**Figure 6**), the main variance is loaded by the PCA-Axes 1 (49.17%) and 2 (25.15%). The groups highlighted by the cluster analysis are confirmed and are clearly differentiated by the PCA plot of the two main axes. PCA-Axis 1 contrasts harbours dominated by fluvial influences (positive scores) and harbours dominated by coastal/marine processes (negative scores). PCA Axis-2 characterizes the different harbour management strategies. Negative values are related to important human pressures on the shoreline in Antiquity while the harbours with modest human impacts are characterized by positive figures.

<u>3. Presentation of the typology</u>

The different forcing agents can be grouped according to their relationship to the river (floods and sedimentary inputs), the sea (storms and RSL changes) or human societies (dredging and harbour work). In this section, we present the different types of geomorphological contexts exploited by human societies for their harbours. We highlight the key potentialities of these contexts for harbour activities but also the main processes affecting the basins.

Rivers were, in ancient times, pivotal commercial and transport interfaces, between the coastline and the hinterland. Their key role explains why many important ancient cities were located in deltaic contexts, such as the important harbour network of Narbonne in connection with the Bages-Sigean lagoon. The city, founded in 118 BC at the crossroads between terrestrial (Via Domitia and Via Aquitania), maritime and fluvial (Aude/Garonne) axes was a pole of international trade. The harbour city attracted many ship owners and traders, and Narbonne was one of the most active harbours in the Roman Empire (Sanchez and Jézégou, 2011).

3.1. Fluvial harbours

The cluster analysis undertaken on the dataset includes the fluvial harbours (Arles, Pisa, Halmyris) in Group C, in addition to other harbours primarily subjected to flood hazards (e.g. river-mouth harbours). Fluvial harbours were generally located on riverbanks (e.g. channel levees). They were affected by episodic events such as floods but also by sedimentary infilling and channel mobility that played out over longer time scales.

The main fluvial harbour of Pisa (Tuscany, Italy) has been intensely investigated in recent decades, highlighting the importance of fluvial activity on the evolution of harbour structures (e.g. Benvenuti *et al.*, 2006, 2009; Allinne *et al.*, 2016). Pisa was an important Etruscan city integrated into the Roman Republic during the 3rd century BC. The fluvial harbour "Stazione Pisa-San Rossore", located close to the ancient city shows the constraints on fluvial harbours and the challenges that societies faced to adapt to these (**Figure 7A**). According to Benvenuti *et al.* (2006) and Bruni (2000), the succession of floods led to the successive migration of the river course (palaeo-meander of the Serchio River) towards the Northwest and led to the destruction of numerous installations and ships. This channel was used as a harbour from the 5th century BC until the 5th or the 6th centuries AD, before its complete infilling and eventual abandonment (Camilli and Setari, 2005). Several flood-damaged wrecks have been dated between the 2nd century AD and the 5-6th centuries AD. It seems clear that the harbour basins were relocated in tandem with the migration of the channel towards the north-west. This translates the adaptation of the inhabitants to river migration more than to flood risk (Allinne *et al.*, 2016). The city of Pisa was strongly affected by river floods due to the dense and complex network of fluvial channels related to the Arno and Serchio rivers. Bini *et al.* (2015) have identified three different river channels in the city area (**Figure 7.C**) and have shown that, in Etruscan and Roman times (5th century BC – 2nd century AD), inhabitants expanded Pisa's urban network following the spatial distribution of topographically elevated areas, mainly formed by a complex and unstable fluvial network.

In a similar vein, the wreck of a Roman barge discovered in the Rhone River at Arles (Bouches-du-Rhone, France) further attests to the importance of floods on ancient fluvial harbours. Vella (2011) and Vella *et al.* (2014) have described erosion surfaces typical of an increase in fluvial dynamics at the top of cores drilled below the wreck. This erosion surface is followed by a coarse sedimentation that culminated with the sinking of the boat around 50-66 AD (Vella, 2011). The wreck, lying between 4 and 9 m depth, was overlain by fluvial sediments, including ceramics from the 1st/2nd centuries AD (Long, 2009a). A longitudinal cross-section undertaken in the Grand Rhone, at the wreck site, underlines an artificial bank elevation of around 3.2 m during the 1st century AD (Mellinand and Sivan, 2011). The bank was reinforced at this time, possibly due to increasing harbour activity in this area of the river (Vella *et al*., 2014). The stability of the bank is attested by the 19th century docks that are located above the Roman bank (Vella *et al*., 2009).

Geoarchaeological investigations by Giaime *et al*. (2018b) reveal that the settlement of Halmyris (Danube Delta, Romania) exploited a secondary palaeo-channel of the Saint-George arm of the Danube River during Antiquity (**Figure 8**). The presence of this channel, characterized by chironomids and ostracods living in flowing waters, partially explains the location of the Getic settlement (6th – 1st centuries BC), followed by the Roman fortress (1st – 7th centuries AD). Due to its sheltered position, Halmyris was protected from Danube flooding. The disconnection of the Halmyris channel from the main Saint-George branch of the Danube appears contemporaneous with the abandonment of the settlement during the 7th century AD.

These examples present different aspects of flood hazard management during Antiquity. Pisa's harbour engineers chose to build light structures, which could be easily rebuilt when the channel shifted course. Archaeological excavations undertaken in the fluvial basins have demonstrated that the artificial structures were composed of wood and no "hard" harbour installations (quays, artificial banks) have been discovered (Allinne *et al*., 2016). At Arles, however, a flood management strategy seems to have been preferred. This scheme is reflected by the stabilisation of the riverbank during the 1st century AD. Around 2000 years ago, the hydrological activity of the Rhone was important. Arnaud-Fassetta and Landuré (2014) have demonstrated that the mean discharge was high and several high-energy flood episodes have been recorded. Nevertheless, the number of overbank flooding events affecting the city was reduced after the elevation of the banks (Bruneton *et al*., 2001; Vella *et al*., 2014). By contrast, Halmyris had a slightly elevated position compared to the surrounding delta plain and was naturally protected from Danube floods. Furthermore, in comparison to Arles and Pisa, the harbour was built in a low-energy river channel. The main pressure on the harbour of Halmyris was subsequently linked to the siltation and the migration of the channel.

<u>River-mouth harbours</u>

Fluvial harbours are/were used by vessels adapted to fluvial navigation, which transported goods that were often unloaded in river-mouth harbours (Boetto, 2010). Since Early Antiquity, fluvial mouths have been used as safe havens, notably during storms (Raban, 1985).

The use of river mouths as shelters dates back to the Bronze Age at least, with possible examples on the coast of Israel including Nahariya, Tel Achziv, Tel Akko or Tel Abu Hawam. However, over the long term, such environments were vulnerable to a plethora of natural hazards, both of marine and terrestrial origin (Anthony, 2009). Hydrological, sedimentological, biological and human processes interact and can induce domino effects on the environment. The infilling and mobility of a river-mouth environment can have an upstream or a downstream origin because such environments are affected by fluvial discharge and marine-sediment deposition, even in the Mediterranean's micro-tidal regime. The vulnerability of river-mouth harbours to numerous hazard types explains why the cluster analysis did not clearly isolate an estuarine group within the dataset. River-mouth harbours are clearly delineated in Group A (Tel Akko – Bronze and Iron Age) which demonstrates the impact of sedimentary inputs into lagoonal-estuary environments, where this anchorage was located. We also identified two river-mouth harbours in the "fluvial group" (Group C) related to the importance of fluvial activity in their management (Castélou/Mandirac and Ostia). The importance of RSL changes in the geomorphological evolution of two river-mouth harbours is also discernible for the submerged sites of Herakleion and Les-Saintes-Maries-de-la-Mer found in Group B.

Raban's (1985) hypothesis for Levantine harbours is confirmed for the harbours of Tel Akko (Haifa Bay, Israel). Imported archaeological material (Egypt, Cyprus, the Aegean) demonstrates that the city must have had a harbour since the Bronze Age (Artzy and Beeri, 2010; Artzy, 2012; Artzy *et al.*, submitted). At that time, a lagoon-type estuary was used as an anchorage area (Morhange *et al.*, 2016c; Giaime *et al.*, 2018a). Bio-sedimentological analyses have shown that this environment was permanently connected to the sea and constituted a good natural anchorage area. The gradual closure of the lagoon, probably driven by the morphogenesis of a sand spit and its infilling by sediments transported by the Na'aman River, engendered the relocation of the anchorage on the open coast (the western façade of the tell in Late Persian/Early Hellenistic times).

Geoarchaeological research undertaken in Ostia (mouth of the Tiber River, Italy) reveals the close relationships between the city and the river since its foundation during the late 4th/early 3rd centuries BC (Salomon *et al.*, 2017, 2018; **Figure 9**). Significant deltaic progradation associated with fluvial changes since Roman times led to the progressive infilling of the channel and of the related harbour facilities. Located in the immediate proximity of the castrum in the 4th century BC, the channel migrated to the north in the 1st century BC (Salomon *et al.*, 2017). Although two small harbour basins have been identified along the river at Ostia, it seems that most of the city's riverbanks were used as a harbour canal (Goiran *et al.*, 2014; Sadori *et al.*, 2016; Salomon *et al.*, 2018). In one of the fluvial channels, an abrupt facies change between the pre-harbour facies and the harbour facies, associated with a chronological gap, suggests that the harbour basin was possibly excavated 6 m below Roman sea level and adapted for large maritime ships (Goiran *et al.*, 2014). Nonetheless, heavy tonnage boats were probably unable to navigate up the river to the harbour because of offshore bars at the mouth of the Tiber (Boetto, 2010; Goiran *et al.*, 2014; Salomon *et al.*, 2014). As early as the 1st century AD, the basin was infilled by flood deposits (Goiran *et al.*, 2014; Sadori *et al.*, 2016) and the water column was reduced to 0.5m rendering the harbour obsolete (Goiran *et al.*, 2014). The construction of Portus' harbour complex (Claudius' basin) in the central part of the delta, inaugurated by the Emperor Nero in 64 AD, overcame the environmental challenges of the river-mouth harbour at Ostia. This new deltaic harbour allowed the area to retain its role as a leading port city in Roman Imperial times.

The importance of rivers, and their associated lagoons, has been highlighted for the Roman city of Narbonne (Aude, France; Sanchez *et al.*, 2014, in press; Faïsse *et al.*, 2018). The ancient Bubresus lake (nowadays Bages-Sigean lagoon; **Figure 10**) constituted an ideal natural environment to accommodate a harbour. The lagoon was protected from the sea and had a water depth of at least 3 meters in Early Roman times (Faïsse *et al.*, 2018; Sanchez et al., *in press*). This explains the high density of Roman settlements located on the palaeo-islands and the waterfront of the lagoon. In the Augustan period (27 BC – 14 AD), 50 sites (of the 124 archaeological sites identified for the period) were (30 sites) or could have been (20 sites) used for harbour purposes (Carayon *et al.*, 2017). The fluvial harbour of Narbonne could be accessed by boat through the southern arm of the Aude River (that roughly corresponds to the present position of the Robine Canal). The first major installations on the channel mouth are dated to the 1st century AD (Sanchez *et al.*, in press). Two parallel artificial jetties, ~2 km long, were built on fluvial sandbanks (Faïsse *et al.*, 2018; **Figure 10 C-D**). The two jetties (15-25 m wide) were ~50 m apart and built to maintain a 3.5-4 m deep channel (Mathé *et al.*, 2016; Faïsse *et al.*, 2018; Sanchez *et al.*, in press). They were equipped with quays to unload and transfer goods from large maritime vessels to shallow-draught fluvial ships, or to be transported by terrestrial roads. Because of the intense fluvial sedimentary inputs, Roman engineers reduced the width of the northern part of the channel in order to increase the flow velocity and avoid siltation of the channelized course (Faïsse *et al.*, 2018; Sanchez *et al.*, in press). Archaeological excavations along these jetties have demonstrated that they were probably extended several times in order to keep the entrance of the channel clear of sediment. The fragility of these structures is attested by numerous repairs during the Early Roman Empire and explains the construction of a breakwater on the eastern side of the channel, to protect the area from swell (Sanchez *et al.*, in press).

Group B incorporates river-mouth harbours (Herakleion, once located in the former Canopic mouth of the Nile and Les-Saintes-Maries-de-la-Mer, today submerged off the coast of the Rhone Delta). These two harbours are characterised by high fluvial sediment supply that led to the formation of deltaic lobes where the harbours were hosted. RSL changes and the silting of the former channels led to the eventual destruction of the lobes.

Geomorphological investigations on the Rhone Delta (France) have shown that, in Antiquity, the delta's coastline was locally more advanced in the sea, due to the location of the mouth of the Saint-Ferréol arm of the river (Vella *et al.*, 2005; Arnaud-Fassetta and Provansal, 2014). Some three kilometres seaward, the discovery of several ancient wrecks allowed researchers to reconstruct the morphology of the palaeo-mouth of the ancient Rhone of Saint-Ferréol (**Figure 11**). The wrecks were grounded on off-shore bars formed at the mouth of the river whilst trying to enter the channel (Long, 2009b). The Saint-Ferréol branch of the Rhone was one of the major arms of the river in Antiquity and numerous ancient deltaic settlements lay on the banks of the channel (Arnaud-Fassetta and Landuré, 2014). One important anchorage seems to have been located in this part of the delta between the 5^{th} century BC and the 5^{th} century AD. Long and Duperron (2011) have excavated anchors and limestone blocks, up to 10 m below present mean sea level, interpreted as possible relics of harbour constructions (Long, 2009b). The subsidence of these harbour structures is associated with an erosion of the deltaic lobe induced by a strong reduction in sediment supply following the upstream infilling of the Saint-Ferréol branch that started during the second part of the 1^{st} century AD (Arnaud-Fassetta and Landuré, 2014).

Shoreline retreat and deltaic subsidence are important in explaining the evolution of the Canopic mouth of the Nile River (western Nile Delta, Egypt), where the ancient harbours cities of Herakleion and Eastern-Canopus were located (**Figure 12**). Archaeological and geophysical investigations have highlighted the presence of harbour structures and shipwrecks up to 6 m below present mean sea level (Goddio, 2010; Hamouda *et al.*, 2015; Robinson and Goddio, 2015). "Sediment failure" has been evoked to explain this subsidence, including the cumulative impacts of earthquakes, Nile floods or high-energy events, in addition to human constructions on unconsolidated sediments (Stanley *et al.*, 2004, 2006). By contrast, recent work by Flaux *et al.* (2017a) has elucidated two periods of negative sediment budget at the Canopic mouth. The first, between 5500 and 4000 BP, was linked to a decrease in Nile discharge. The second phase occurred during the last 500 years, leading to a significant decrease in the sedimentary budget of the Canopic lobe and an erosion of the promontory. Relative sea-level rise linked to the compaction and liquefaction of unconsolidated muds culminated in the complete submersion of the promontory. The morphology of the Canopic river mouth, a promontory extending out into the sea, made it particularly exposed to high-energy events. Flaux *et al.* (2017a) identified two marine intrusions, recorded in the Canopic lobe's closed-lagoon environments, dated to the 1st and 2nd-3rd centuries AD that could correspond to high-energy events having affected Alexandria (Goiran, 2012).

The different examples highlighted above show that river-mouth harbours are located in challenging geomorphological contexts. In the short term, both fluvial floods and marine storms can affect them. At longer timescales, fluvial sediment budgets play a major role in shaping their geomorphological evolution (Flaux *et al.*, 2017a). The two submerged estuarine harbours, Herakleion and Les-Saintes-Maries-de-la-Mer, highlight that these environments are extremely sensitive to rapid relative sea-level rise and a decrease in sediment supply. Nevertheless, the vast majority of ancient river-mouth harbours are today landlocked on deltaic plains. Good examples include the harbours of Ravenna and Classe (Emilia Romagna, Italy) separated from the sea by the morphogenesis of a large coastal spit, or the harbour of Lattara (Languedoc-Roussillon, France) whose decline was partially induced by the progradation of the Mosson and Lez Rivers into the coastal lagoons (Sabatier *et al.*, 2010).

Lagoonal harbours

Lake and lagoon environments were particularly attractive locations for harbours during Antiquity (see Morhange *et al.*, 2015, 2016a for further references). On the basis of our statistical analyses, most of the lagoonal harbours are found in group A (Cumes-Licola, Pollentia, Orgame, Portus Pisanus, the inner harbour of Seleucia Pieria). Included in this group is the unique example of Maryut lagoon's ancient harbours (e.g. Portus Mareoticus, Taposiris Magna, Marea-Philoxenia). Cumulatively, these port systems constituted the lacustrine harbour of Alexandria, and were located in a mixed lagoonal system that was affected by seasonal Nile floods (Group C). We demonstrate that these environments, while being naturally protected from the sea, were relatively short-lived due to long-term problems of harbour accessibility.

Lagoons, isolated from the sea by coastal spits formed by longshore drift processes, are an important component of Holocene deltas. Such a landscape is still visible on the Danube Delta (Romania), namely the large Razelm-Sinoe lagoon complex, or at a larger scale in the Kuban Delta (Taman peninsula, Russia). Today, lagoons constitute around 6400 km^2 of the Mediterranean coastline (Cataudella *et al.*, 2015), but their surface areas were even more significant in Antiquity. In fact, due to base-level sedimentary inputs, most have been totally or partially infilled (Boyd *et al.*, 1992; Oertel *et al.*, 1992; Nichols and Boon, 1994; Duck and Figueiredo Da Silva, 2012). This phenomenon is particularly evident on the Kuban Delta where various authors have reconstructed the transformation of the former Taman archipelago into a peninsula, shaped by the progressive infilling of the former Bosphorus channels linking the Black and the Azov Seas (Brückner *et al.*, 2010; Kelterbaum *et al.*, 2011; Fouache *et al.*, 2012; Giaime *et al.*, 2014 and 2016; **Figure 13**).

Founded in the 7th century BC, the ancient city of Orgame is located on the shores of the Razelm-Sinoe lagoon (southern Danube Delta, Romania). This important lagoon was formed by the reworking of Danube sediments, transported in particular by the Saint-George and Dunavăţ arms of the river and reworked by longshore drift to form several generations of coastal spits that progressively isolated the lagoon from the sea (Giosan *et al.*, 2006; Vespremeanu-Stroe *et al.*, 2017; **Figure 14**). The isolation of the lagoon has been elucidated using sedimentary cores extracted from the harbour basin of Orgame (Bony *et al.*, 2015). The presence of a natural inlet, allowed the populations to exploit a calm water body directly connected to the sea. The large surface area of the lagoon explains why the anchorage area of Orgame was not rapidly infilled. The transformation of the area into a phragmites wetland, and the infilling of the harbour, only began around 1000 years ago because of the influence of the Dunavăţ pro-delta (Bony *et al.*, 2015). The ancient harbour of Orgame is therefore unique in the history of lagoonal harbours in the Mediterranean/Black Sea world because most of the lagoonal harbours have been infilled and landlocked since Antiquity.

Kaniewski et al. (2018) have elucidated that the harbour of Portus Pisanus (the main harbour of Pisa) located north of the city of Livorno (Tuscany, Italy) was hosted in a marine lagoon that gradually evolved into a coastal lake (**Figure 7.D-E**). The development of the protected lagoon started around 200 ± 30 BC in relation to the formation of a sand spit, fed by fluvial sediment reworked by the longshore currents. In Roman times, the lagoon water body was well protected from the sea and had a good connection with the sea, which made the area perfect for maritime transport and trade. There is no evidence of environmental changes until 1000 ± 20 – 1250 ± 20 AD when the lagoon started to lose its connection to the sea because of coastal progradation. The port was completely isolated from the sea in the late 13th century AD.

Numerous ancient lagoonal harbours were rapidly infilled by sediments during Antiquity, leading to the loss of harbour functions for many settlements. This explains why lagoon harbours in deltaic contexts were generally used for a short period of time. The formation of the lagoon of Cumes-Licola (Campania, Italy) resulted from the growth of a sand spit built by the sediments of the Volturno River, to the north of the Cumes palaeo-promontory (**Figure 15**). This lagoon constituted a good environment for a harbour because it was naturally protected from the sea. However, geomorphological investigations have demonstrated that, since Hellenistic times, the lagoon shows signs of rapid infilling because of the erosion of surrounding hillslopes linked to the development of agriculture (Stefaniuk *et al.*, 2003; Stefaniuk and Morhange, 2010). Further infilling led to an important reduction in the water depth of the lagoon. With a depth of <1 m from Late Antiquity onwards, the lagoon was no longer accessible to ships.

The ancient lagoon of *Pollentia* (Mallorca, Balearic Archipelago, Spain), believed to have hosted one of the city's ancient harbours, underwent a similar evolution (Giaime *et al.*, 2017; **Figure 16**). The palaeo-lagoon is located downstream of the northern littoral cell of Alcúdia Bay, north of the mouth of the Muro fluvial system. Due to its shallow water depth, the lagoon was probably dredged at the time of its foundation in the 1st century BC. Nevertheless, its accessibility remained limited and maritime ships would have been anchored offshore, near the Alcanada islet, some 4 km from the lagoon. The use of lighters, between the outer harbour and the lagoon harbour, linked the two areas.

Lake Maryut (Mareotis), which lies behind Alexandria on the western margin of the Nile Delta, hosted a great diversity of harbour structures during Antiquity (**Figure 17**). Archaeological surveys undertaken on the shores of the Maryut have demonstrated that a large part of the lagoon was equipped with jetties related to artisanal or agricultural sites and that several main harbours were located on the lake's waterfront (Blue *et al.*, 2011; Rodziewicz, 2011). At Taposiris Magna (**Figure 17.B**), access to the Roman harbour was restricted by funnel-shaped entrance and exit areas, linked by a 1.7-km-long channel (Boussac and El-Amouri, 2010; Tronchère *et al.*, 2012). The harbour of Marea-Philoxenia comprises a 2-km-long pier intersected by several quays constructed at right angles to the shoreline to form separate basins. These docking areas were active between the 5th and 7th centuries AD, for pilgrimage and trading purposes. The considerable length of the quays made year-round docking possible despite seasonal differences in the Maryut's water level (up to 1.5m) driven by Nile floods. The fluvio-lagoonal system of the Maryut was divided into different geographical and trading areas, with the lacustrine harbour of

Alexandria (Portus Mareoticus) being the focal point. Recent work by Flaux *et al.* (2017b) has highlighted the archaeological potential of Alexandria's lacustrine waterfront in Roman times. Combining bio-sedimentological analyses of sedimentary archives, the study of ancient maps and historical descriptions of the area (mainly from Strabo; Strabo 17.7), Flaux *et al.* (2017b) have highlighted the presence of two areas probably related to Portus Mareoticus (**Figure 18**). They identified at least three ancient jetties, perpendicular (nowadays buried below the present urban fabric of Alexandria) to the lake's shoreline. These structures are several hundred meters long and were used from the 1st century BC to Late Roman times.

These examples demonstrate that the size of the lagoon and the importance of sedimentary input by local rivers are key factors in shaping the continuity of the harbours installed in such contexts. The reconstructed history of Portus Pisanus shows that societies successfully exploited the natural potentiality of a coastal lagoon to host an important harbour system from the 2nd century BC to the 11-12th centuries AD. The lagoon of Cuma-Licola and Pollentia highlight the role of limiting factors (i.e. limited accommodation space) that can affect the accessibility and the navigability of smaller lagoons. At Pollentia, the lagoon was perfectly located, at the foot of the city, but its depth, despite dredging, never allowed large maritime ships to moor there. For the Cuma-Licola lagoon, the mobility of the inlet, associated with the width of the sand spit and the presence of nearshore bars suggests that it was not ideal for naval circulation and for the installation of sustainable harbour activity throughout Antiquity. This explains why many of the region's harbours were located far from the Volturno River, such as Pozzuoli, Baiae or Misenum (Morhange *et al.*, 2015). Maryut lagoon constitutes an interesting case of harbour duality, with both fluvial and lagoonal characteristics. It necessitated specific facilities to accommodate intra-lagoonal navigation. The lagoon decreased in size after its isolation from the Nile and the Mediterranean Sea, from the 9th century AD onwards (Flaux *et al.*, 2012). Settlement of the Mareotis waterfront decreased considerably from the 8th century AD onwards. Nonetheless, no environmental causal link has been directly established and this abandonment could be related to the progressive decline of the use of fluvial transport in addition to a decrease in the political importance of Alexandria after the Arab conquest.

<u>Artificialisation of the harbours</u>

Numerous Roman harbours have been densely artificialized which demonstrates the importance of human activities in maintaining harbour access routes and links to the open sea. During the Roman period, this often necessitated considerable port infrastructure. One example is the dense human artificialization of the Aude river-mouth to stabilize its riverbanks for port activities (**Figure 10**). The Group G determined by the cluster analysis also includes densely equipped harbour basins. These harbours are characterised by the importance of human constructions and the dredging operations needed to maintain a sufficient water depth for maritime circulation in a context of shoreline progradation. In addition, we detailed the case of Alexandria's maritime harbours that were densely artificialized during Late Hellenistic/Roman times but that are nowadays submerged due to the subsidence of the Nile Delta front (Group B). In Magnus Portus (Eastern Harbour), in particular, a plethora of ancient port structures are now submerged. During the Hellenistic-Roman period, harbour infrastructure was diversified. An artificial diversion of one of the arms of the Küçük Meanders River was ordered by Hadrian in the Early 2nd century AD, in order to prevent the siltation of the harbour channel (Kraft *et al.*, 2011; Stock *et al.*, 2016).

During the 1st-2nd centuries BC, the discovery of hydraulic mortar led to a revolution in the construction of harbours along clastic coasts (Hohlfelder and Oleson, 2014). Hydraulic mortar was probably discovered in the Campi Flegrei region of Italy, and was used for the harbours of the Naples Gulf, and then later for *Portus*, the harbour complex of Rome during the 1st century AD (**Figure 9**).

Initiated by Claudius, the construction of the first basin started in 42 AD in order to provide Rome with a maritime harbour, directly linked to the city via the Tiber River. Fifty years later, Trajan furnished the harbour with a second basin dug to the east of the Claudian basin. The Claudian basin, due to its location in the centre of the Tiber Delta front, was directly (1) exposed to wave action, (2) subjected to river floods and (3) to rapid sedimentation. The Portus complex was connected to the Tiber via several channels (Salomon *et al.*, 2014; Lisé-Pronovost *et al.*, 2018). The depth of the Claudius basin was around 6-8 m at the time of its construction and it was adapted to the mooring of large maritime ships (Goiran *et al.*, 2010, 2011). Sedimentary cores have revealed that the sediments trapped in the harbour were mostly sandy, testifying to a large opening to the sea and high-energy dynamics. Despite the impressive moles that protected the harbour basin (**Figure 9**), this facies differs from the common harbour facies found in protected harbours (Marriner and Morhange, 2006a). This hypothesis is reinforced by the writings of Tacitus who describes the destruction of around 200 ships following a storm in 62 AD (Tacitus, Annals, 15.18.2: "*There was no addition to the price, although about* ***two hundred ships were destroyed in the harbour by a violent storm****, and one hundred more, which had sailed up the Tiber, by an accidental fire*"). This situation could explain Trajan's decision to build a second inner basin

(Trajan's harbour) to provide better anchorage for boats. Goiran *et al.* (2011) have revealed, by coring the channel connecting the two basins, a reduction in the energy towards Trajan's basin, marked by a decrease in the sediment grain size. The basin resembles a lagoon environment directly linked to the river and to the sea. The abandonment of Trajan's harbour is documented by an infilling of the channel between the end of the 2nd century AD and the 5th century AD whereas, at that time, the Claudian basin was still navigable with a 5-m water column (Goiran *et al.*, 2011). The example of Portus perfectly illustrates the importance of hydraulic mortar in facilitating the construction of large waterfront harbours. It explains the significant number of harbours built using this method since the 2nd century BC in the Mediterranean (Brandon *et al.*, 2014).

The artificial structures of the ancient harbours of Alexandria also highlight the importance of Pozzolana. After Alexander the Great's conquest of Egypt and the foundation of Alexandria in 331 BC, two harbour basins were constructed on the leeward side of Pharos Island (**Figure 18**). This area was perfect for maritime harbours because it was partially protected by the sandstone ridge (Pharos Island) that acted as a natural breakwater. The existence of the two harbours is attested on either side of the tombolo formed after the construction of an artificial causeway (*Heptastadium*) linking Pharos Island to the continent (Goiran, 2005; Marriner *et al.*, 2008). The Eastern harbour (Magnus Portus) is known to have been densely artificialized during the Roman period, as recounted by Strabo (Geography, 17.1.6-17) who explains that the Eastern Bay was divided into several harbour basins (Hohlfelder and Brandon, 2014). The constructions continued after Strabo's visit of Alexandria, as confirmed by the structures in pumiceous ash from Pozzolana and dated to the 1st century AD, currently drowned in the basin (Hohlfelder and Brandon, 2014). Harbour structures are nowadays submerged in the Eastern basin (Goddio and Yoyotte, 2008; Goddio and Masson-Berghoff, 2016). Stanley *et al.* (2006) have suggested that the submersion of these structures was probably accentuated by their construction on unconsolidated coastal sediments. The cumulative impact of natural hazards, such as earthquakes, storm waves and tsunamis probably also played a role in the destabilisation of the sediments.

In deltaic contexts, Pozzolana structures have been used to protect harbours. The harbour of Forum Iulli, in the modern city of Frejus (Var, France) is a landlocked harbour presently located ca. 1.5 km from the coast. The harbour was first mentioned in 31 BC (Tacite repeated by Pliny the Older Annals 4.5), when Frejus harbour hosted part of Antony and Cleopatra's fleet, captured by Octavian after the battle of Axium. No archaeological structures related to the harbour are earlier than the Augustan period (end of the 1st c. BC – beginning of the 1st c. AD; Gébara and Morhange, 2010). In Roman times, Frejus was located on the eastern limit of the Argens Ria, at the palaeo-mouth of the Argens and Reyran Rivers (**Figure 19**). Due to its position, at the margin of the Argens-Reyran river mouth, the harbour experienced problems of silting (Excoffon et al., 2010) that necessitated regular dredging (Bony et al., 2011). In order to control the sedimentary infilling of the basin, inhabitants also built a jetty to prevent sediments from filling the harbour entrance. Excoffon and Dubar (2011), have highlighted the use of pozzolana in the construction of this jetty, built in the continuity of the southern mole of Frejus harbour (**Figure 19**).

4. The geoarchaeological trajectory of ancient deltaic harbours

The geomorphological trajectories of ancient harbours in deltaic contexts show that early coastal societies favoured natural anchorages along the coast (lagoons, river-mouths). Independently of any deltaic influence, such naturally protected areas are scarce, which necessitated the development of early harbour engineering. Marriner *et al*. (2014) have reported the early artificialisation, beginning in the Bronze Age, of pocket beaches along the coast of the Levant. The examples of Tyre, Sidon and Beirut clearly show the evolution of harbour infrastructure in their sediment records (Ancient Harbour Parasequence; Marriner and Morhange, 2006; Marriner *et al*., 2014). In deltaic contexts, the utilisation of naturally protected areas did not require such man-made harbour protection systems, at least in Early Antiquity. Furthermore, rapid deltaic progradation since the Bronze Age did not allow the perpetuation of harbour activities in such areas. This means that the different sediment facies are not vertically stacked because of the relocation of the harbour basins through time, to keep pace with the shifting delta front. At Ephesus (Western Anatolia), intensive geoarchaeological work undertaken during the past two decades reveals the succession of at least six different harbours from the Late Bronze to Late Byzantine periods (**Figure 20**). The first anchorages (Sacred and Koressos harbours) had few man-made structures. This is attested by the absence of a classic harbour sequence (Marriner and Morhange, 2006), the sediments comprising marine sands that are consistent with a progradational sequence (Kraft *et al*., 2007; Stock *et al*., 2014). Use of these areas - since the 11th century BC for the Sacred harbour and since the mid-8th century for the Koresian harbour - are attested by ceramics and the contemporaneous multiplication of riverine settlements along the coast, showing a clear parallel between harbour location and settlement patterns. The same link is visible at Tel Akko (Haifa Bay, Israel; Artzy, 2012; Morhange *et al*., 2016; Giaime *et al*., 2018a; Artzy *et al*., submitted). In this maritime trade city, largely occupied (and urbanized) from the Middle Bonze Age onwards, the settlement pattern is linked to fluvio-coastal changes and harbour displacement. Former harbour activities were concentrated in the lagoonal estuary of the

Na'aman River during the Bronze and Iron Ages before their relocation to the western façade during Persian times. Subsequently, sometime between the late 3rd or the beginning of the 2nd century BC, the tell was abandoned following the relocation of the harbour on the Akko promontory, 1.5 km away and beyond the influence of fluvial processes. The absence of artificial structures at the two sites is explained by the natural protection of the anchorages.

At Ephesus, the harbours' location at the back of the transgressed ria meant that they were well protected from coastal storms. At Akko, the lagoonal-estuary was well sheltered. At both Akko and Ephesus, the artificial harbour constructions are attested from the Hellenistic period onwards. At Akko, a mole was constructed to protect the harbour basin from the swell. The harbour was then extended in Roman and Medieval times, because Akko was an important harbour city and the Hellenistic basin is still in use today (Galili *et al.*, 2010; Galili and Rosen, 2017). The heart of the Anatolian city was definitively moved and intensive constructions started on the western side of Mount Pion during the Hellenistic period. At the same time, the first harbour structures seem to have been constructed. The artificial mole built during the middle-Hellenistic period was lengthened and possibly reinforced at several stages during Roman times (Kraft *et al.*, 2007). Nonetheless, the widespread human interventions (constructions and dredging) on the harbour basin were not sufficient to prevent the siltation of the basin, whose accessibility was drastically reduced in Late Roman and Byzantine times. In the end, the harbour could only be accessed by small, shallow-draught vessels. Maritime boats had to be unloaded in natural anchorages downstream.

Deltaic contexts did not significantly affect the evolution of harbour structures (Marriner *et al.*, 2014). By contrast, harbours and their associated settlements had to regularly be relocated to keep abreast with deltaic progradation, which has led to the term "race to the sea" being coined.

5. Conclusion

This typology has shed light on the evolution of ancient harbour basins in deltaic contexts. Each geomorphological context presents specific advantages and disadvantages. The earliest harbours were hosted in naturally protected areas. In deltaic contexts, river mouths were preferred, but such environments were poor long-term harbours because of the combined action of sedimentary inputs, river changes and high-energy fluvial and marine events. Nonetheless, ancient populations developed techniques to improve or maintain the natural potentialities of their anchorage areas, before the discovery of hydraulic mortar and the construction of more grandiose harbour complexes along coastlines lacking natural anchorages.

Despite floods, storms and sedimentary inputs, human populations adapted to these changing and, at times, challenging environments. Nevertheless, human responses to environmental modifications were highly variable. The “race to the sea” seems to have been the norm in Antiquity, sometimes leading to the complete abandonment of settlements and their relocation in areas less vulnerable to deltaic progradation.

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Figure 1: Location of the sites (harbours or deltas) discussed in this manuscript.

Figure 2: A. Palaeogeography of the progradation of the Acheloos delta since 600 BC and the location of the harbours of Oiniadai (Trikardo palaeo-island) mentioned in the text (adapted from Vött et al., 2007). B. Regional location of the site.

Figure 3: A. Geomorphological map of the Gialias ria (adapted from Devillers, 2008). B. Regional location of the site.

Figure 4: Dredging scars from the ancient harbour of Naples (Viviana Liuzza, Soprintenza arceologica di Napoli (A) and (B) Carsana et al., 2009). C. Leonardo da Vinci sketch depicting a dredging machine (draga cavafango; Manoscritto E, foglio 75 v.)

Figure 5: Heat-map and associated cluster analysis of the ancient harbour dataset. The cluster analysis allowed us to distinguish four different groups (A to D) based on the importance of the environmental and/or anthropogenic forcings that affected the harbour basins. Details of the database are given in the Supplementary Material.

Figure 6: Principal Components Analysis of the database. The figure presents the distribution of the harbour sites studied according to the importance of each environmental and/or anthropogenic pressure identified. The groups correspond to the cluster analysis results. The histograms denote the weight of each characteristic for Axis-1 and Axis-2.

Figure 7: A. Geomorphological map of the Pisan deltaic plain and location of the different harbours (adapted from Bini et al., 2015; Allinne et al., 2016; Kaniewski et al., 2018). B. Regional location of the site. C. Location of the palaeo-channels of the Serchio and the Arno rivers around the Etruscan/Roman city of Pisa (Prehistoric channels are denoted in yellow, Etruscan/Roman channels in light blue and Mediaeval channels in light grey; adapted from Bini et al., 2015; Image Microsoft Bing Maps). D-E. Landscape reconstruction showing two evolutionary stages of the lagoon of Portus Pisanus as documented by historical sources and archaeological data (adapted from Kaniewski et al., 2018). (D) Roman period - a wide lagoon basin, hosting Portus Pisanus as mentioned in literary sources. (E) late Middle Ages - the accretion of arcuate beach ridges, belonging to the Arno Delta strandplain, led to the closure of the lagoon. Construction of the maritime harbour of Livorno in a seaward position with respect to the lagoon.

Figure 7: A. Geomorphological map of the Danube delta close to Halmyris. The figure highlights the favourable location of Halmyris, on an elevated area and close to the palaeo-channel where the harbour was located in Getic (6th – 1st centuries BC) and Roman (1st– 7th centuries AD) times (after Giaime et al., 2018). B. Regional location of the site.

Figure 8: A. Palaeogeography of Ostia's harbour system in Antiquity (adapted from Goiran et al., 2010; 2014; Vittori et al., 2015; Salomon et al., 2017, 2018). The Ostia river-mouth basin was abandoned before the construction of Portus in the 1st century AD. The figure highlights the importance of the Tiber delta's progradational dynamics since Roman times; B. Regional location of the site.

Figure 9: A. Geomorphology of the Bages-Sigean lagoon complex. The red square denotes the location of the Castélou/Mandirac river-mouth facilities (adapted from Faïsse et al., 2018). B. Regional location of the site; Palaeogeographical reconstruction of the Castélou/Mandirac area before the 1st century AD (C), in the 1st century AD (D) when the first structures were built, and in the 5th century AD (E) at the time of the abandonment of the site (adapted from Faïsse et al., 2018).

Figure 10: A. Palaeogeography of the Saint-Ferreol channel of the Rhone Delta (France) in Roman times (adapted from Pagès et al., 2008; survey Luc Long). B. Regional location of the site. C. Scenario for the progradation of the Rhone delta during the past 5000 years (adapted from Vella et al., 2005)

Figure 11: A. Geomorphological features of the Abu Qir Bay/Canopic coast on the western Nile Delta (adapted from Flaux et al., 2017a). The bathymetry of the western bay and the positions of Herakleion and East Canopus are adapted from Goddio (2007). B. Regional location of the site.

Figure 12: A. The ancient Bosphorus of the Taman Peninsula, south-east Russia (adapted from Giaime et al., 2016). B. Regional location of the site.

Figure 13: Palaeogeographical reconstruction of Orgame's coastal landscapes ~3500–2000 yr cal. BP (A) and ~1200 yr cal. BP (B) (adapted from Bony et al., 2015). B. Regional location of the site. The erosion of the promontory to the north of Orgame is attested by the destruction of ancient structures located on the cliff (ca. 20 m in height).

Figure 14: A. Geomorphology of the southern margin of the Volturno Delta and location of the ancient harbour of Cumes in the infilled lagoon of Licola. High sediment supply is attested by the large sand spit which has isolated the lagoon from the sea (adapted from Morhange et al., 2015). B. Regional location of the site.

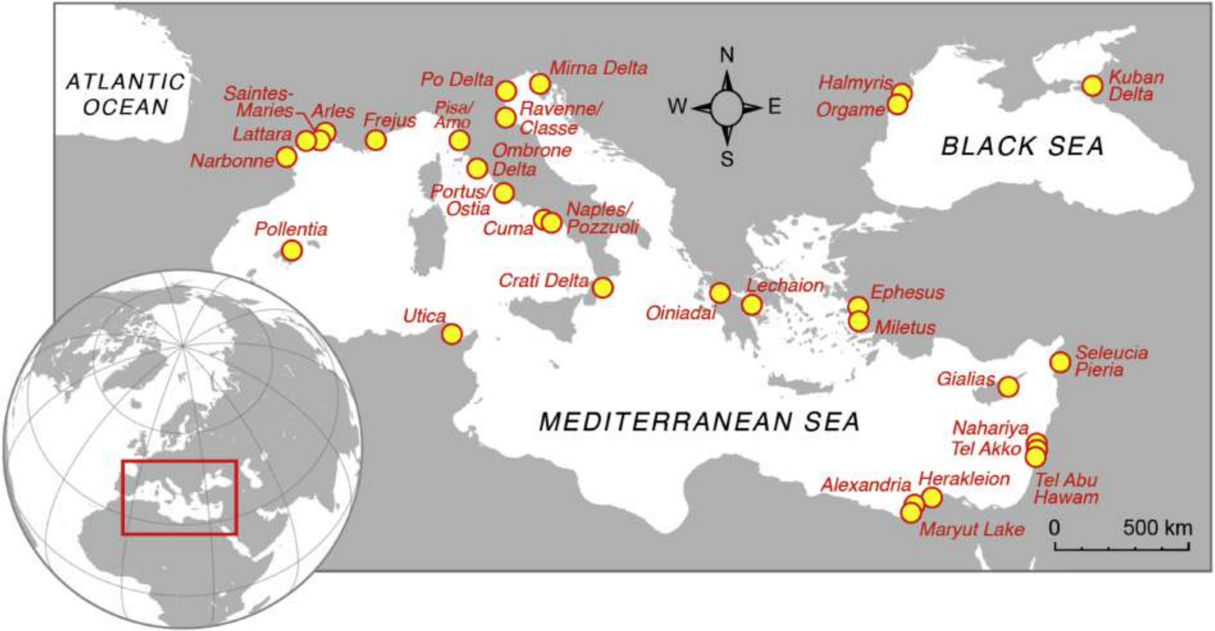
Figure 15: A. Geomorphological map of the ancient lagoon of Pollentia, Mallorca (adapted from Giaime et al., 2017). The harbours were located in the northern part of the lagoon. The ancient inlet was probably located close to the present inlet.

Figure 16: Hydro-geomorphological map of the north-west Nile Delta during Antiquity, showing the location of sites discussed in the text (adapted from Flaux et al. 2017b). B. Regional location of the site. C. Artificial constructions at Taposiris harbour (adapted from Boussac and El-Amouri, 2010; Image: Microsoft Bing Maps).

Figure 17: A. Geomorphological map of Alexandria (Western Nile Delta, Egypt) and the location of its ancient harbours. The figure highlights the accretion of the tombolo after the construction of the artificial causeway (Heptastadium) following the foundation of the city by Alexander the Great in 331 BC (adapted from Goiran, 2001; Marriner et al., 2008; Flaux et al., 2017). B. Regional location of the site.

Figure 18: A. Geomorphological map of the Argens Delta and location of the harbour basin of Frejus on the distal margin of the 11-km-long Holocene ria (adapted from Dubar, 2004). The positions of the successive coastlines in the lower valley are adapted from Bertoncello 2014 (black line: Neolithic coastline; black dashed line: Bronze Age coastline; black dotted line: first Iron Age coastline; red dotted line: second Iron Age coastline; red dashed line: coastline at 0BC/AD; red line: Early Roman Empire coastline). They identified the succession of several beach-ridges and lagoonal environments similar to the current coastal morphology since the Bronze Age. B. Map of the Roman city of Forum Iulii with the location of the structures including volcanic tuff and Pozzolana material (after Excoffon and Dubar, 2011). The position of the coastline in the 1st century AD is from Excoffon et al. (2006) and the position of the coastline in the 1st century AD is from Gébara and Morhange, 2010 (adapted from Bony et al., 2011).

Figure 19: Progradation of the Küçük Menderes (Cayster) deltaic plain since the Neolithic and location of the successive anchorages of Ephesus, the Sacred Harbour (1), Koressos harbour (2), the Roman and Byzantine harbour (3), the Byzantine harbour (4), the Late Byzantine and later harbour (5), Pygela harbour (6) (adapted from Brückner, 2005; Stock et al., 2013).



ATLANTIC OCEAN
BLACK SEA
MEDITERRANEAN SEA
N
W
E
S
Saintes-Maries
Arles
Lattara
Narbonne
Frejus
Pisa/ Arno
Po Delta
Mirna Delta
Ravenne/ Classe
Ombrone Delta
Portus/ Ostia
Naples/ Pozzuoli
Cuma
Pollentia
Crati Delta
Utica
Oiniadai
Lechaion
Ephesus
Miletus
Halmyris
Orgame
Kuban Delta
Seleucia Pieria
Gialias
Nahariya
Tel Akko
Tel Abu Hawam
Alexandria
Herakleion
Maryut Lake
0
500 km

Figure 1

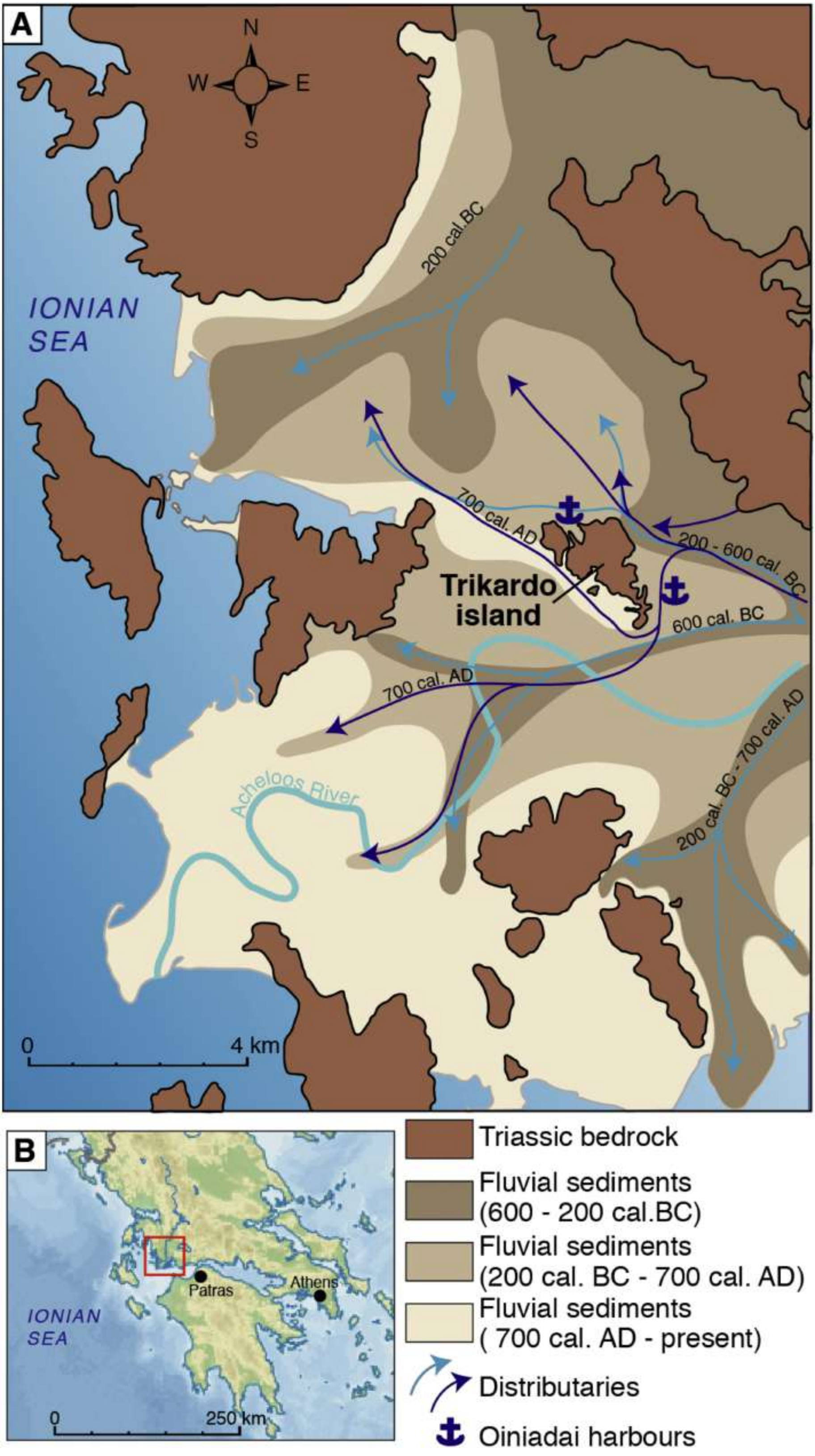

A
N
W
E
S
IONIAN SEA
200 cal.BC
700 cal. AD
Trikardo island
200 - 600 cal. BC
600 cal. BC
700 cal. AD
200 cal. BC - 700 cal. AD
Acheloos River
0
4 km
B
IONIAN SEA
Patras
Athens
0
250 km
Triassic bedrock
Fluvial sediments (600 - 200 cal.BC)
Fluvial sediments (200 cal. BC - 700 cal. AD)
Fluvial sediments (700 cal. AD - present)
Distributaries
Oiniadai harbours

Figure 2

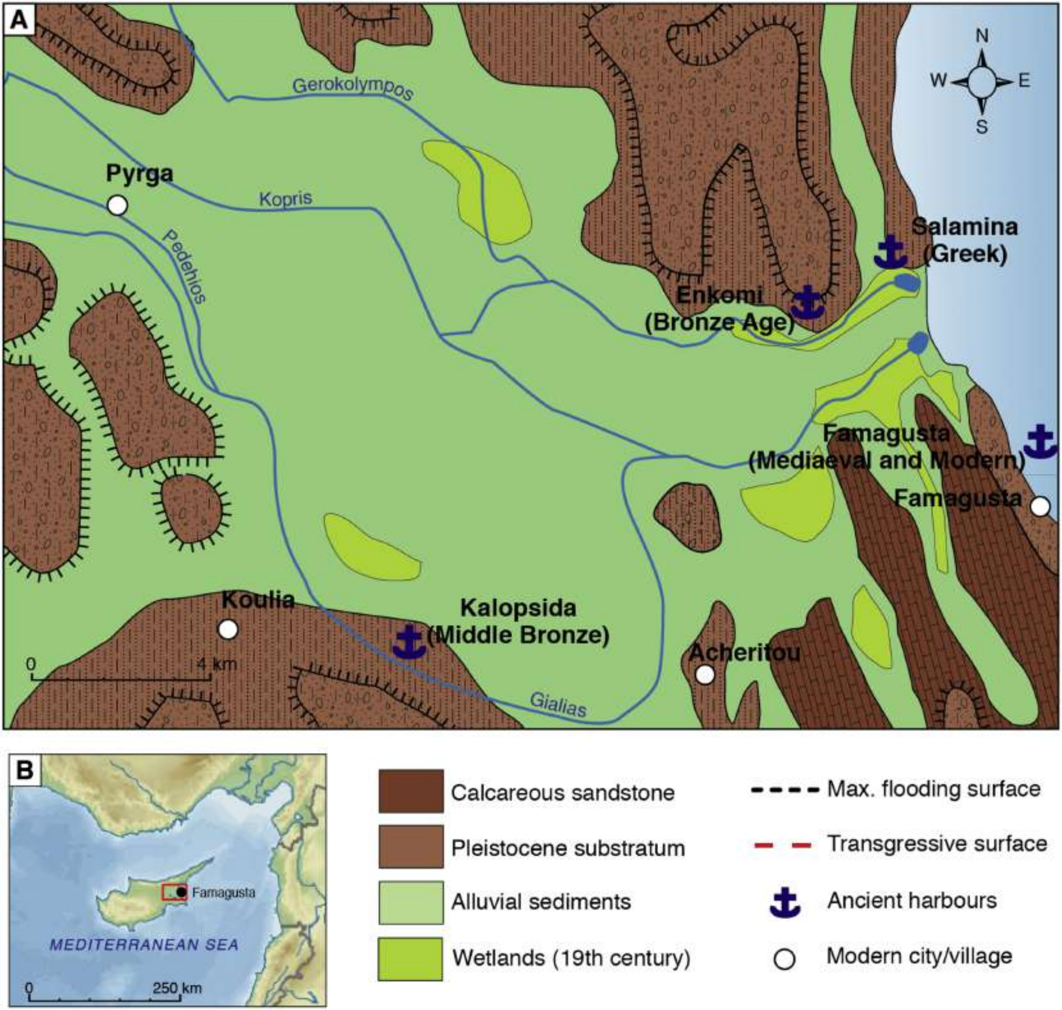

A
Gerokolympos
Kopris
Pedehios
Pyrga
Salamina
(Greek)
Enkomi
(Bronze Age)
Famagusta
(Mediaeval and Modern)
Famagusta
Koulia
Kalopsida
(Middle Bronze)
Acheritou
Gialias
0
4 km
N
S
W
E
B
Famagusta
MEDITERRANEAN SEA
0
250 km
Calcareous sandstone
Pleistocene substratum
Alluvial sediments
Wetlands (19th century)
Max. flooding surface
Transgressive surface
Ancient harbours
Modern city/village

Figure 3

Figure 4

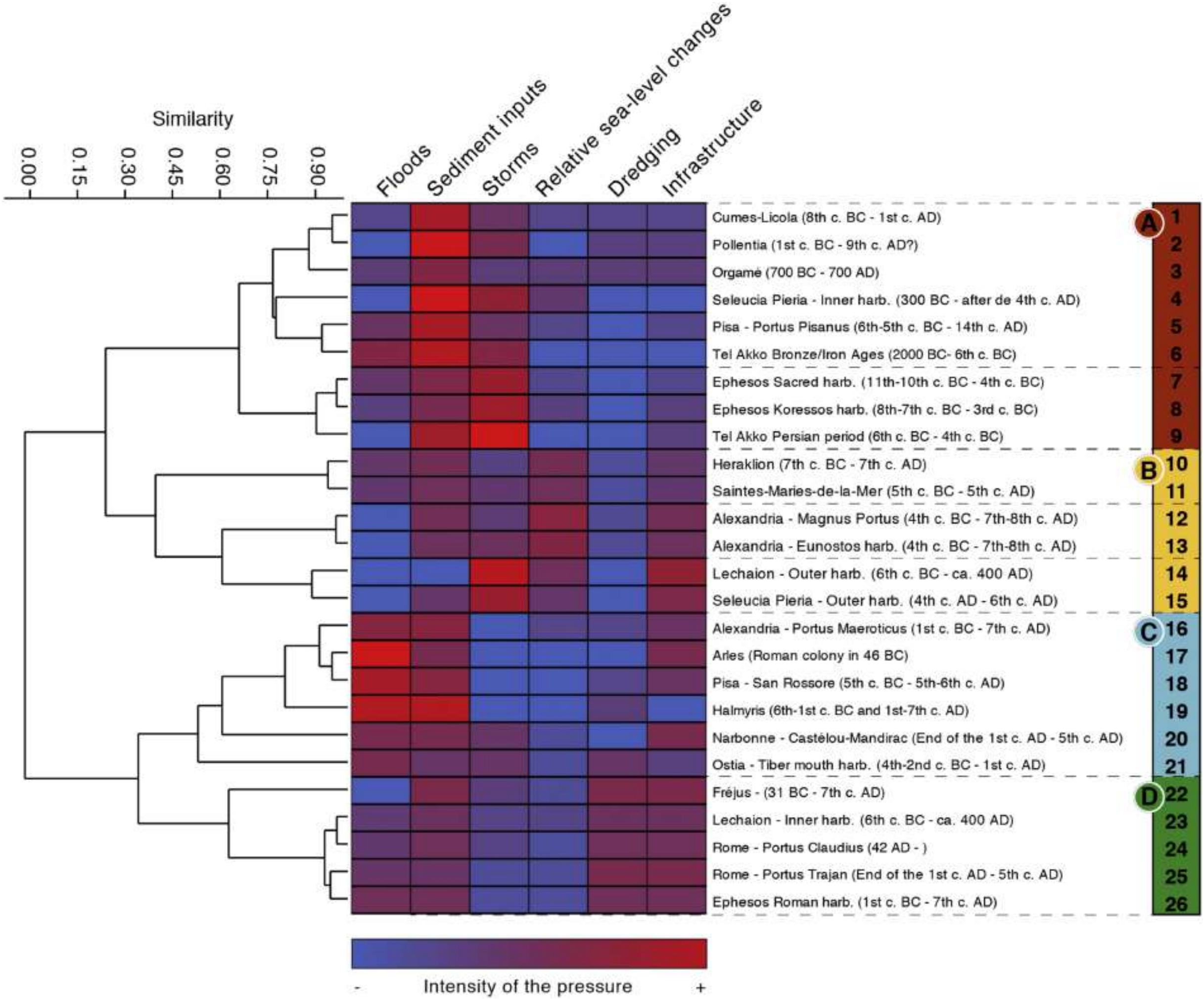
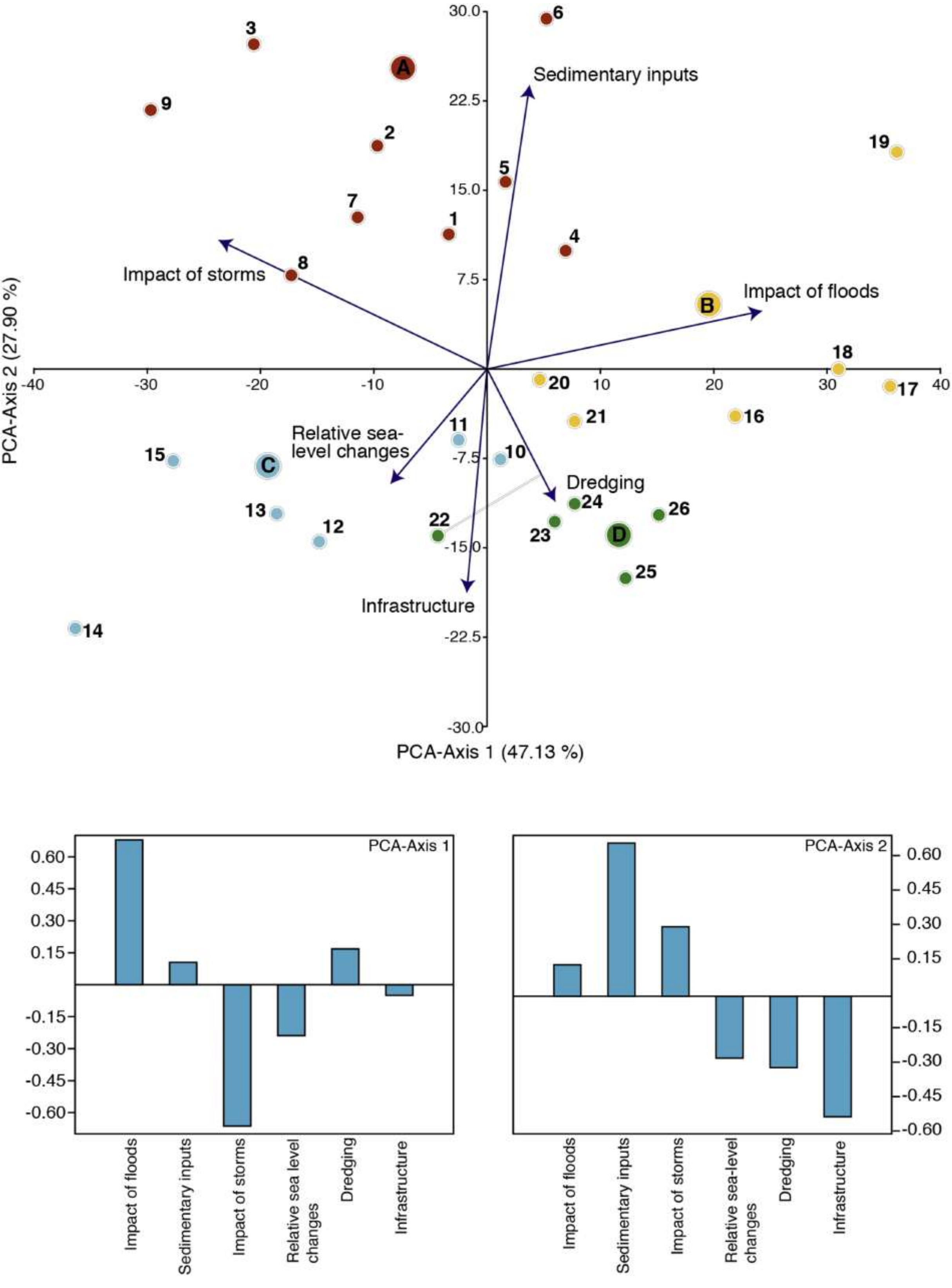
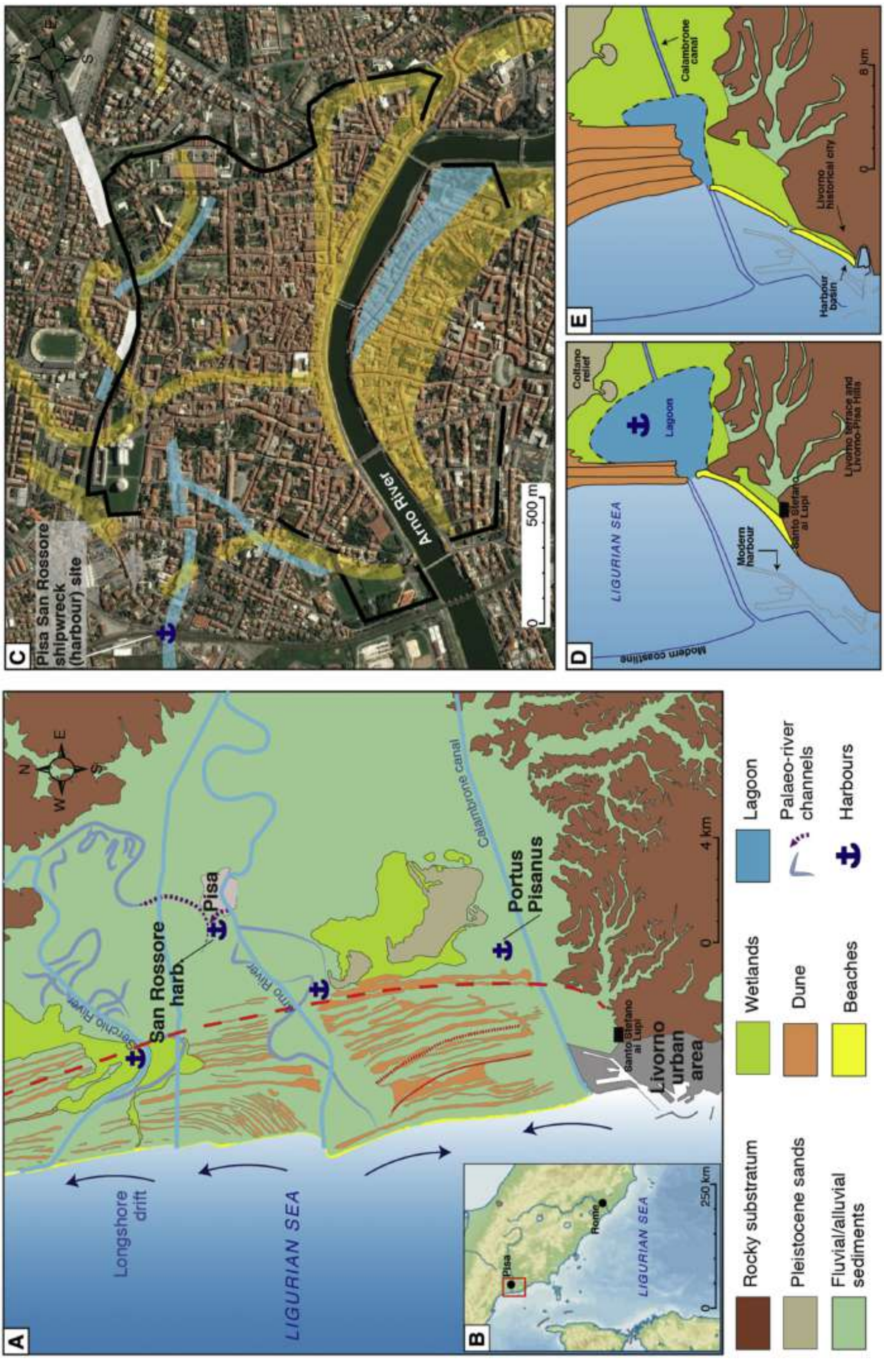

Similarity
0.00
0.15
0.30
0.45
0.60
0.75
0.90
Floods
Sediment inputs
Storms
Relative sea-level changes
Dredging
Infrastructure
Cumes-Licola (8th c. BC - 1st c. AD)
Pollentia (1st c. BC - 9th c. AD?)
Orgamé (700 BC - 700 AD)
Seleucia Pieria - Inner harb. (300 BC - after de 4th c. AD)
Pisa - Portus Pisanus (6th-5th c. BC - 14th c. AD)
Tel Akko Bronze/Iron Ages (2000 BC- 6th c. BC)
Ephesos Sacred harb. (11th-10th c. BC - 4th c. BC)
Ephesos Koressos harb. (8th-7th c. BC - 3rd c. BC)
Tel Akko Persian period (6th c. BC - 4th c. BC)
Heraklion (7th c. BC - 7th c. AD)
Saintes-Maries-de-la-Mer (5th c. BC - 5th c. AD)
Alexandria - Magnus Portus (4th c. BC - 7th-8th c. AD)
Alexandria - Eunostos harb. (4th c. BC - 7th-8th c. AD)
Lechaion - Outer harb. (6th c. BC - ca. 400 AD)
Seleucia Pieria - Outer harb. (4th c. AD - 6th c. AD)
Alexandria - Portus Maeroticus (1st c. BC - 7th c. AD)
Arles (Roman colony in 46 BC)
Pisa - San Rossore (5th c. BC - 5th-6th c. AD)
Halmyris (6th-1st c. BC and 1st-7th c. AD)
Narbonne - Castélou-Mandirac (End of the 1st c. AD - 5th c. AD)
Ostia - Tiber mouth harb. (4th-2nd c. BC - 1st c. AD)
Fréjus - (31 BC - 7th c. AD)
Lechaion - Inner harb. (6th c. BC - ca. 400 AD)
Rome - Portus Claudius (42 AD -)
Rome - Portus Trajan (End of the 1st c. AD - 5th c. AD)
Ephesos Roman harb. (1st c. BC - 7th c. AD)
A
B
C
D
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
-
Intensity of the pressure
+

Figure 5



PCA-Axis 1 (47.13 %)
PCA-Axis 2 (27.90 %)
Sedimentary inputs
Impact of storms
Impact of floods
Relative sea-level changes
Dredging
Infrastructure
A
B
C
D
PCA-Axis 1
PCA-Axis 2
Impact of floods
Sedimentary inputs
Impact of storms
Relative sea level changes
Dredging
Infrastructure

Figure 6



A
B
C
D
E
LIGURIAN SEA
Longshore drift
San Rossore harb.
Pisa
Portus Pisanus
Arno River
Serchio River
Calambrone canal
Santo Stefano ai Lupi
Livorno urban area
Rome
250 km
0
4 km
Rocky substratum
Pleistocene sands
Fluvial/alluvial sediments
Wetlands
Dune
Beaches
Lagoon
Palaeo-river channels
Harbours
Pisa San Rossore shipwreck (harbour) site
500 m
Modern coastline
Modern harbour
Lagoon
Coltano relief
Livorno terrace and Livorno-Pisa Hills
Harbour basin
Livorno historical city
8 km

Figure 7

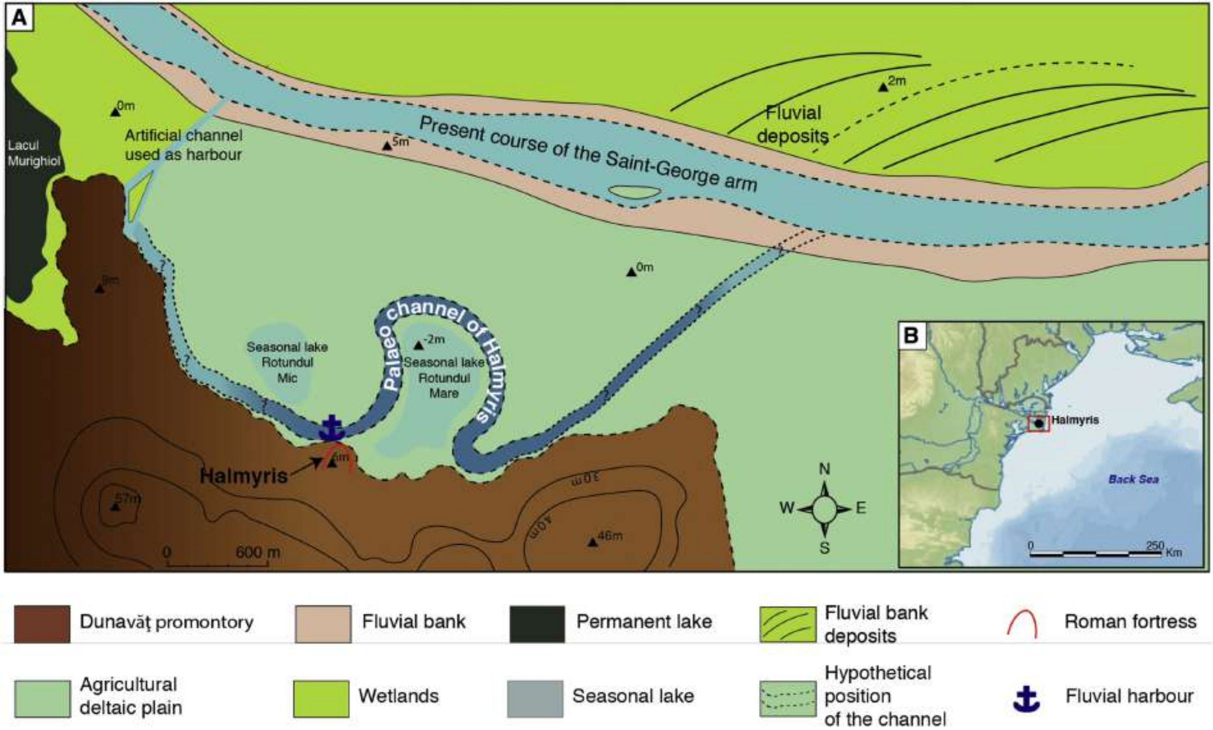
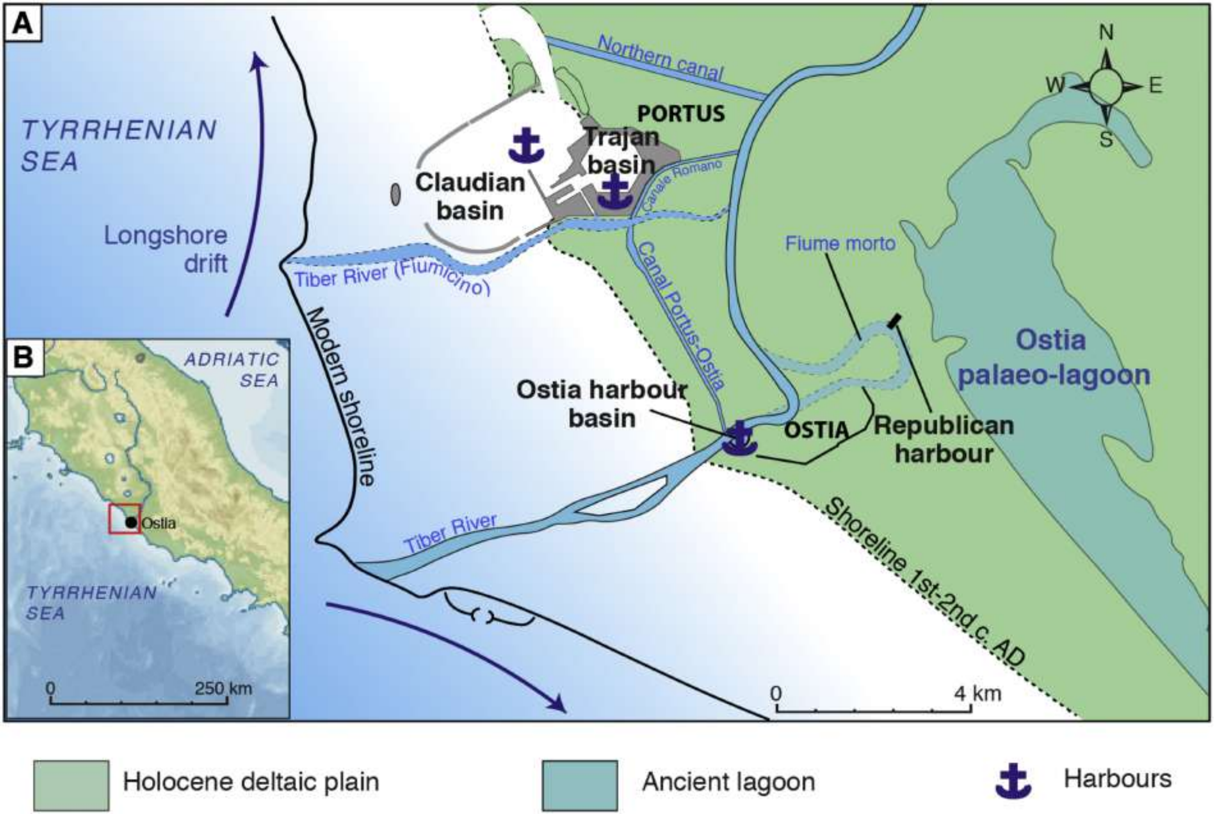

A
Lacul Murighiol
Artificial channel used as harbour
Present course of the Saint-George arm
Fluvial deposits
0m
5m
2m
0m
-2m
Seasonal lake Rotundul Mic
Seasonal lake Rotundul Mare
Palaeo channel of Halmyris
Halmyris
57m
46m
30m
40m
0
600 m
N
S
W
E
B
Halmyris
Back Sea
0
250
Km
Dunavăţ promontory
Fluvial bank
Permanent lake
Fluvial bank deposits
Roman fortress
Agricultural deltaic plain
Wetlands
Seasonal lake
Hypothetical position of the channel
Fluvial harbour

Figure 8



A
B
TYRRHENIAN SEA
Longshore drift
Northern canal
PORTUS
Trajan basin
Claudian basin
Canale Romano
Tiber River (Fiumicino)
Canal Portus-Ostia
Fiume morto
Modern shoreline
Ostia palaeo-lagoon
Ostia harbour basin
OSTIA
Republican harbour
Tiber River
Shoreline 1st-2nd c. AD
N
W
E
S
0
4 km
ADRIATIC SEA
Ostia
TYRRHENIAN SEA
0
250 km
Holocene deltaic plain
Ancient lagoon
Harbours

Figure 9

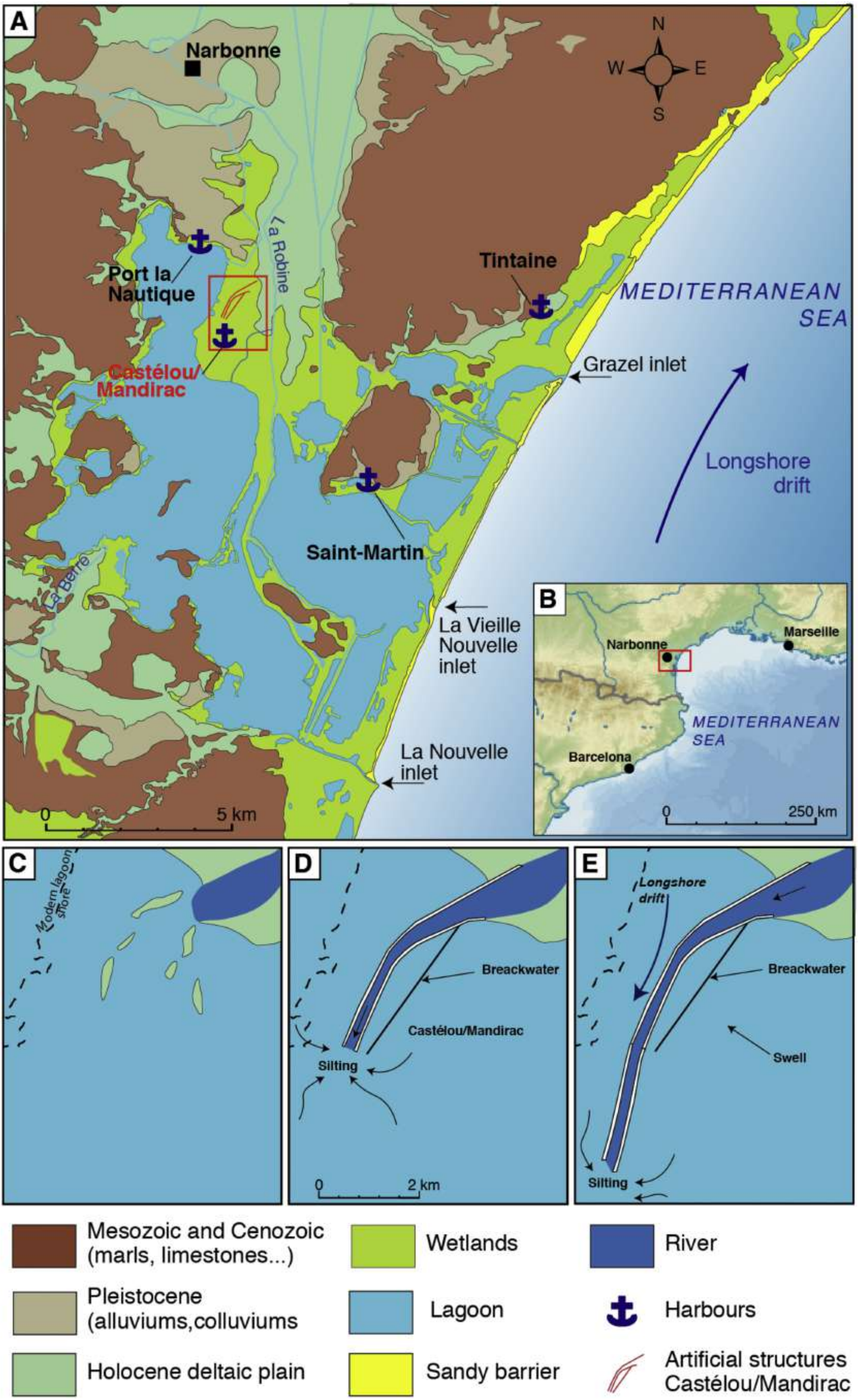

A
Narbonne
N
W
E
S
La Robine
Port la Nautique
Castélou/ Mandirac
Tintaine
MEDITERRANEAN SEA
Grazel inlet
Longshore drift
Saint-Martin
La Berre
La Vieille Nouvelle inlet
La Nouvelle inlet
0
5 km
B
Narbonne
Marseille
MEDITERRANEAN SEA
Barcelona
0
250 km
C
Modern lagoon shore
D
Breackwater
Castélou/Mandirac
Silting
0
2 km
E
Longshore drift
Breackwater
Swell
Silting
Mesozoic and Cenozoic (marls, limestones...)
Pleistocene (alluviums,colluviums
Holocene deltaic plain
Wetlands
Lagoon
Sandy barrier
River
Harbours
Artificial structures Castélou/Mandirac

Figure 10

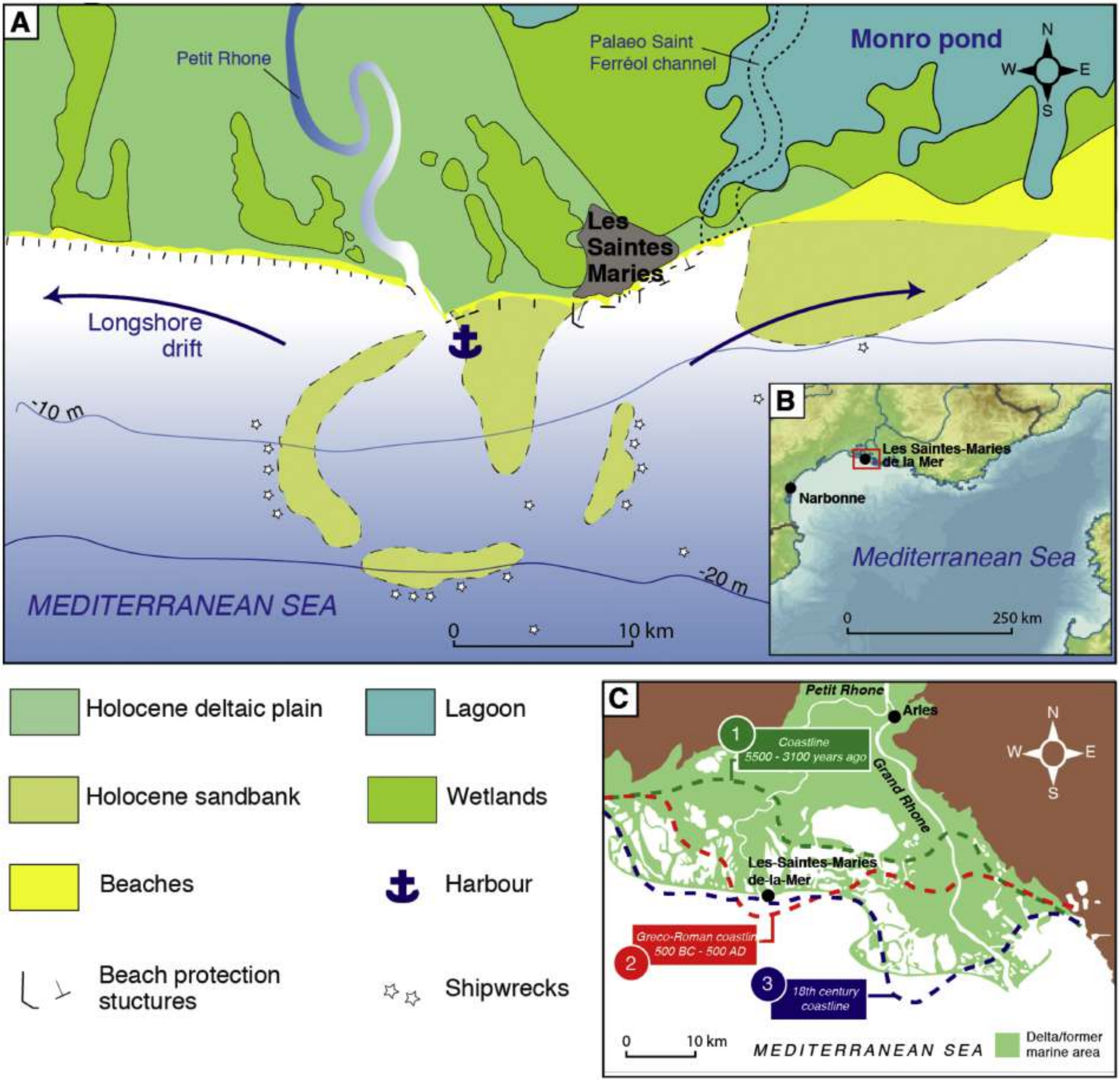

A
Petit Rhone
Palaeo Saint
Ferréol channel
Monro pond
N
W
E
S
Les
Saintes
Maries
Longshore
drift
-10 m
-20 m
MEDITERRANEAN SEA
0
10 km
B
Les Saintes-Maries
de la Mer
Narbonne
Mediterranean Sea
0
250 km
Holocene deltaic plain
Lagoon
Holocene sandbank
Wetlands
Beaches
Harbour
Beach protection
stuctures
Shipwrecks
C
Petit Rhone
Arles
1
Coastline
5500 - 3100 years ago
Grand Rhone
N
W
E
S
Les-Saintes-Maries
de-la-Mer
Greco-Roman coastlin
500 BC - 500 AD
2
3
18th century
coastline
0
10 km
MEDITERRANEAN SEA
Delta/former
marine area

Figure 11

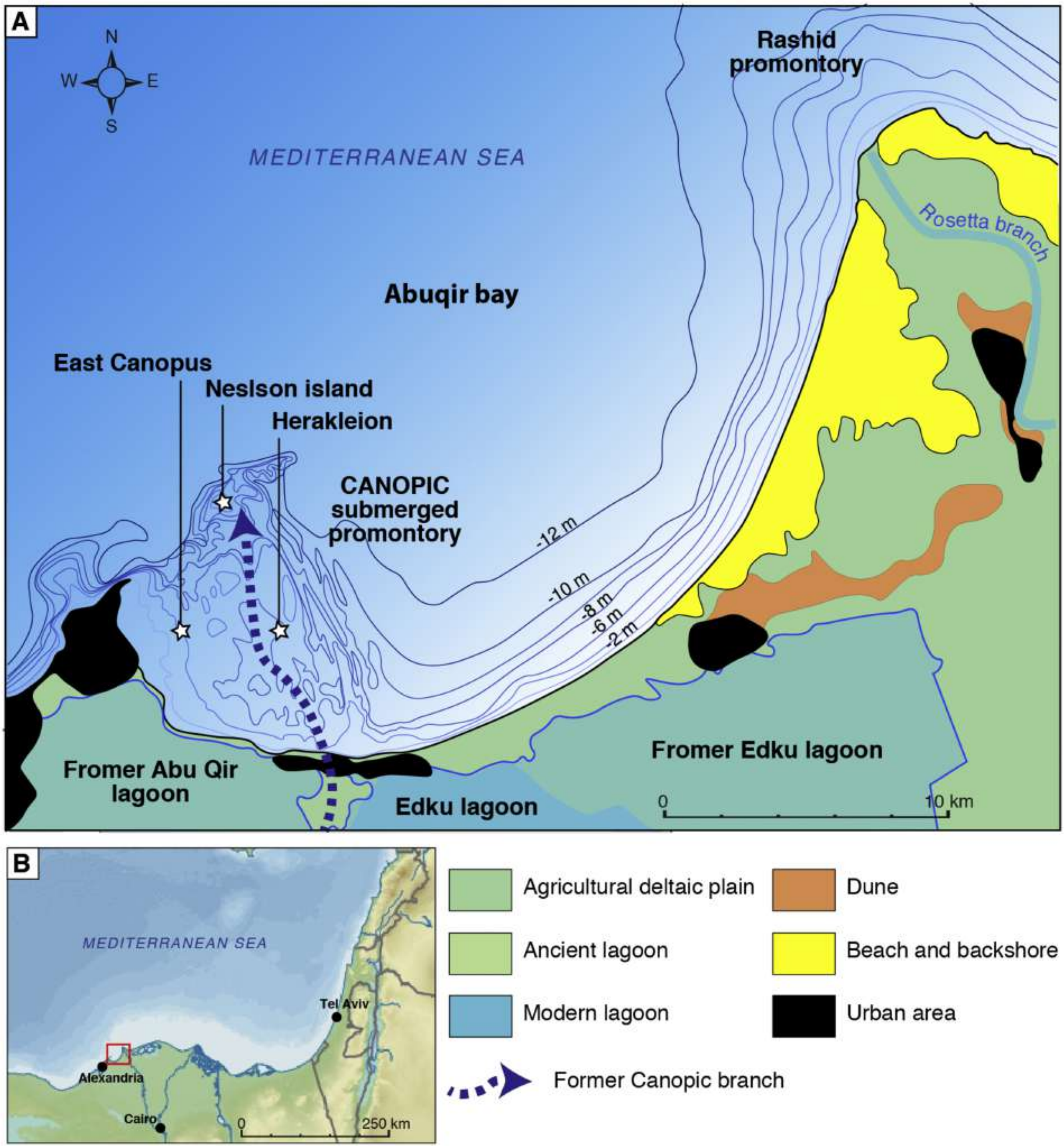

A
N
W
E
S
MEDITERRANEAN SEA
Rashid promontory
Rosetta branch
Abuqir bay
East Canopus
Neslson island
Herakleion
CANOPIC submerged promontory
-12 m
-10 m
-8 m
-6 m
-2 m
Fromer Abu Qir lagoon
Edku lagoon
Fromer Edku lagoon
0
10 km
B
MEDITERRANEAN SEA
Tel Aviv
Alexandria
Cairo
0
250 km
Agricultural deltaic plain
Ancient lagoon
Modern lagoon
Dune
Beach and backshore
Urban area
Former Canopic branch

Figure 12

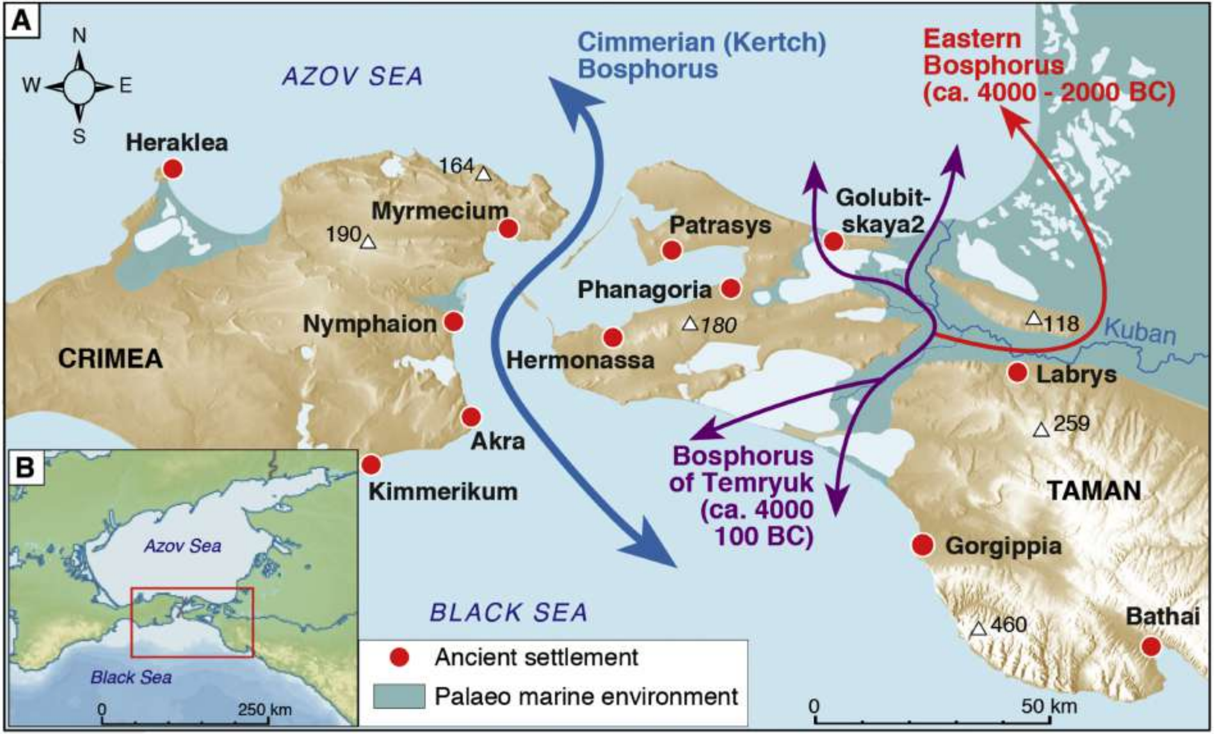

A
N
W
E
S
AZOV SEA
Cimmerian (Kertch) Bosphorus
Eastern Bosphorus (ca. 4000 - 2000 BC)
Heraklea
164
Myrmecium
190
Golubit-skaya2
Patrasys
Phanagoria
Nymphaion
180
118
Kuban
CRIMEA
Hermonassa
Labrys
259
Akra
Bosphorus of Temryuk (ca. 4000 100 BC)
Kimmerikum
TAMAN
Gorgippia
B
Azov Sea
BLACK SEA
Bathai
460
Black Sea
0
250 km
Ancient settlement
Palaeo marine environment
0
50 km

Figure 13

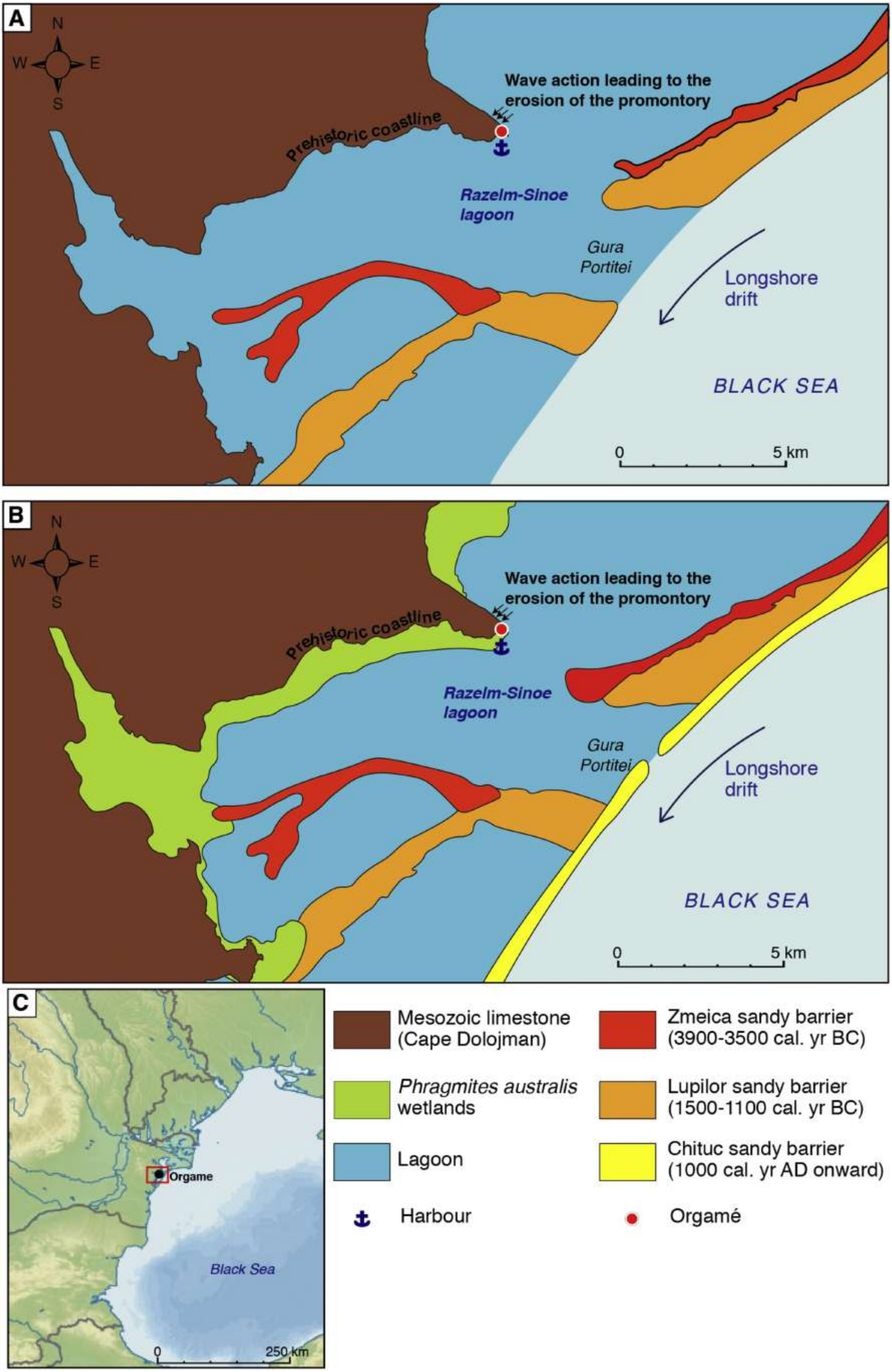

A
N
W
E
S
Wave action leading to the erosion of the promontory
Prehistoric coastline
Razelm-Sinoe lagoon
Gura Portitei
Longshore drift
BLACK SEA
0
5 km
B
N
W
E
S
Wave action leading to the erosion of the promontory
Prehistoric coastline
Razelm-Sinoe lagoon
Gura Portitei
Longshore drift
BLACK SEA
0
5 km
C
Orgame
Black Sea
0
250 km
Mesozoic limestone (Cape Dolojman)
Phragmites australis wetlands
Lagoon
Harbour
Zmeica sandy barrier (3900-3500 cal. yr BC)
Lupilor sandy barrier (1500-1100 cal. yr BC)
Chituc sandy barrier (1000 cal. yr AD onward)
Orgamé

Figure 14


A
Volturno River mouth (12 km North)
Patria lagoon
N
W
E
S
Liternum
B
ADRIATIC SEA
Ostia
Cuma
TYRRHENIAN SEA
0
250 km
Longshore drift
Ancient lagoon of Licola
Cuma
Monte Nuovo
Lucrino lagoon
Fusaro lagoon
Puzzuoli
Torre Gavetta
Misenum
Monte di Procida
TYRRHENIAN SEA
0
3 km
Tufa
Pyroclastic rocks
Pyroclastic deposits
Sandy-loam Holocene deposits
Palustral deposits in volcanic crater
Dune
Beaches
Modern lagoon
Ancient lagoon
Cuma harbour

Figure 15

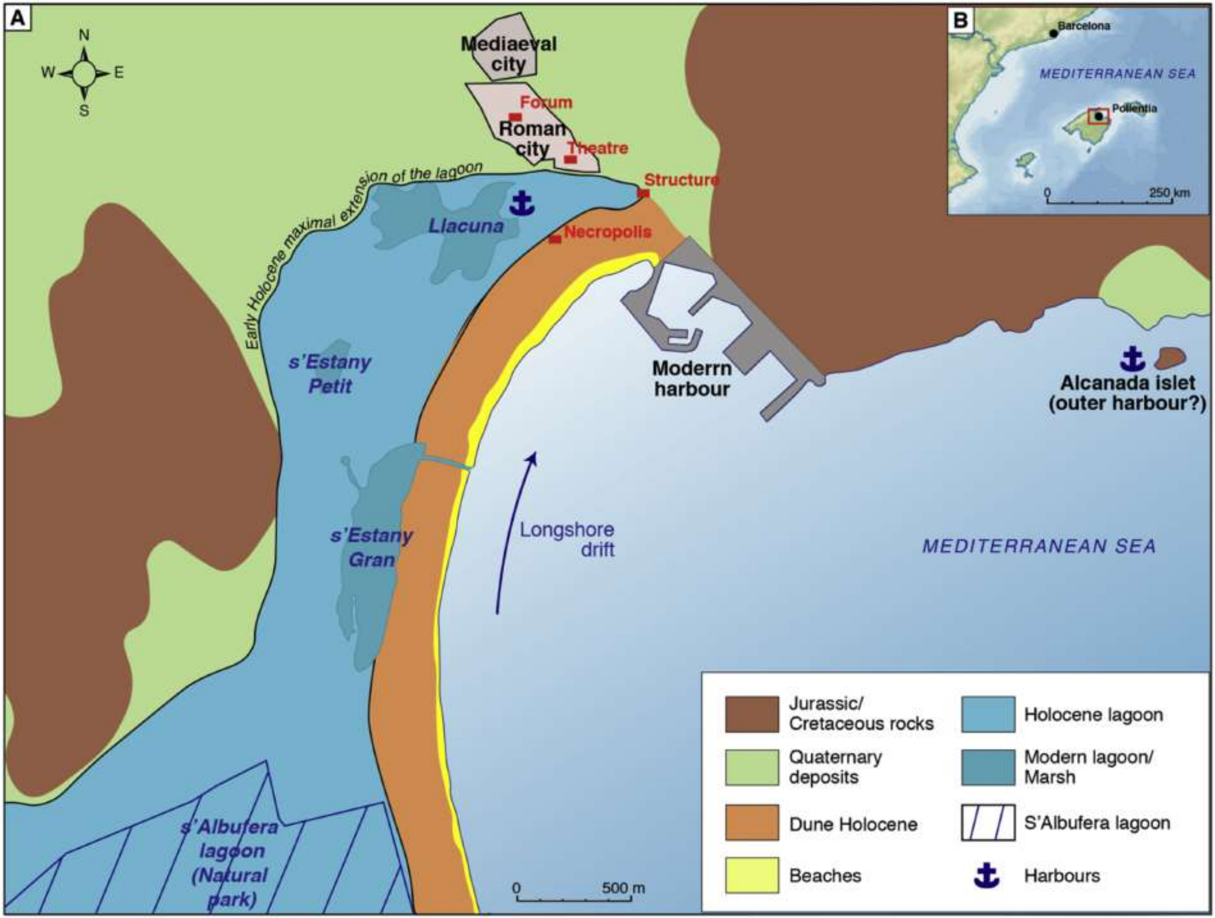

A
N
W
E
S
Mediaeval city
Forum
Roman city
Theatre
Structure
Early Holocene maximal extension of the lagoon
Llacuna
Necropolis
s'Estany Petit
Moderrn harbour
Alcanada islet (outer harbour?)
Longshore drift
s'Estany Gran
MEDITERRANEAN SEA
s'Albufera lagoon (Natural park)
0
500 m
Jurassic/ Cretaceous rocks
Quaternary deposits
Dune Holocene
Beaches
Holocene lagoon
Modern lagoon/ Marsh
S'Albufera lagoon
Harbours
B
Barcelona
MEDITERRANEAN SEA
Pollentia
0
250 km

Figure 16

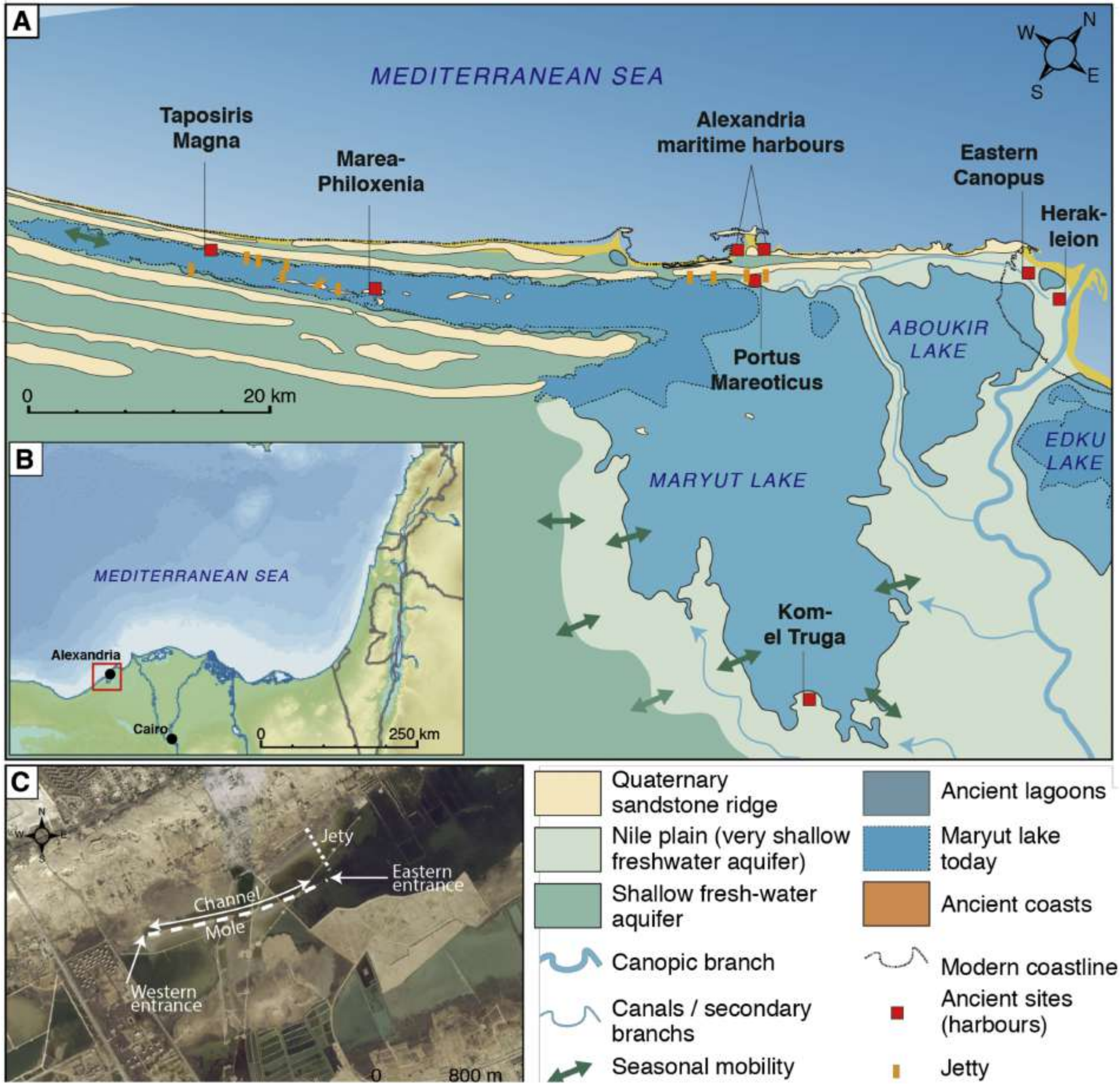

A
MEDITERRANEAN SEA
N
W
E
S
Taposiris Magna
Marea-Philoxenia
Alexandria maritime harbours
Eastern Canopus
Herak-leion
Portus Mareoticus
ABOUKIR LAKE
EDKU LAKE
MARYUT LAKE
Kom-el Truga
0
20 km
B
MEDITERRANEAN SEA
Alexandria
Cairo
0
250 km
C
Jety
Eastern entrance
Channel
Mole
Western entrance
0
800 m
Quaternary sandstone ridge
Nile plain (very shallow freshwater aquifer)
Shallow fresh-water aquifer
Canopic branch
Canals / secondary branchs
Seasonal mobility
Ancient lagoons
Maryut lake today
Ancient coasts
Modern coastline
Ancient sites (harbours)
Jetty

Figure 17

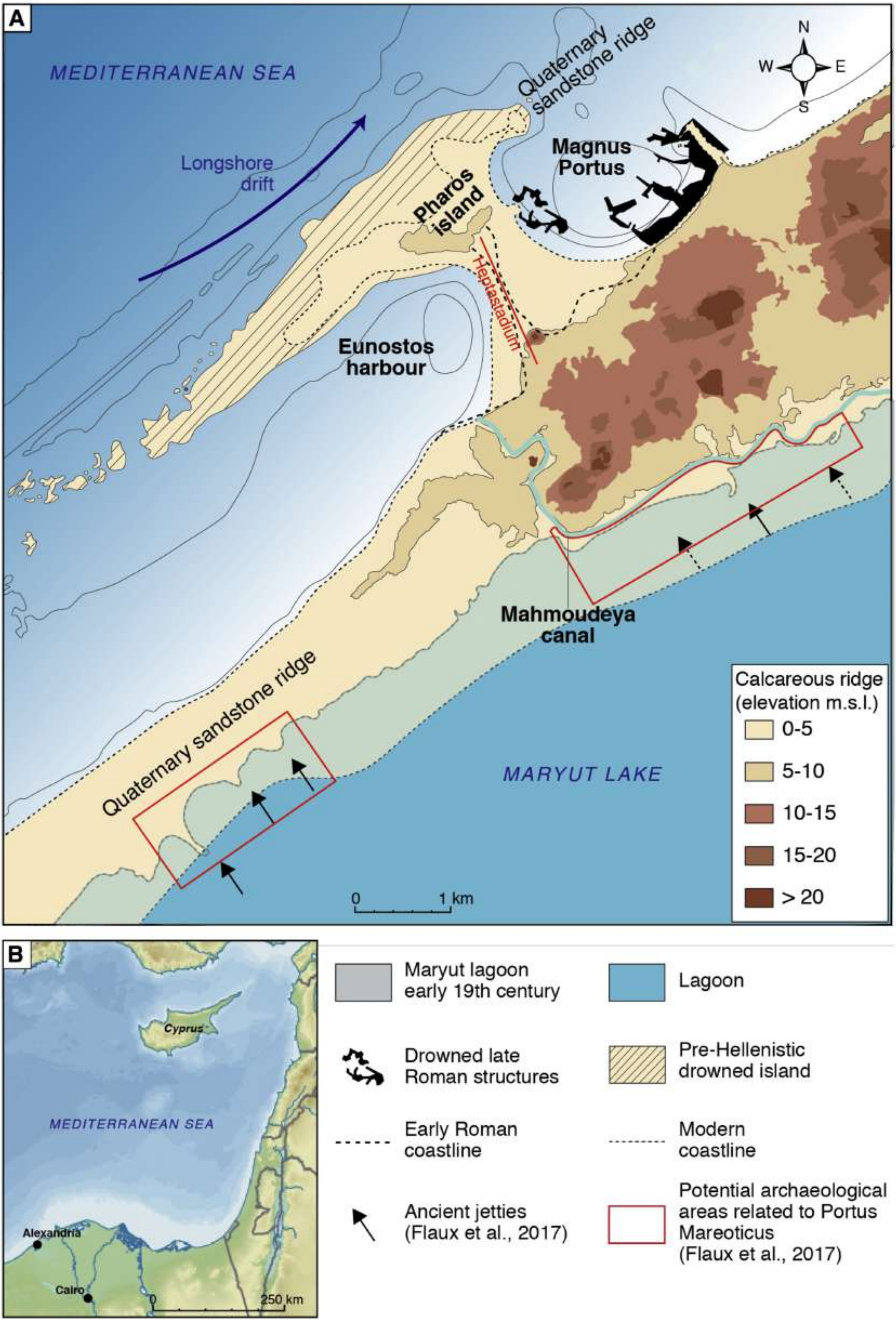

A
MEDITERRANEAN SEA
Quaternary sandstone ridge
N
W
E
S
Longshore drift
Magnus Portus
Pharos island
Heptastadium
Eunostos harbour
Mahmoudeya canal
Quaternary sandstone ridge
MARYUT LAKE
Calcareous ridge (elevation m.s.l.)
0-5
5-10
10-15
15-20
> 20
0
1 km
B
Cyprus
MEDITERRANEAN SEA
Alexandria
Cairo
0
250 km
Maryut lagoon early 19th century
Lagoon
Drowned late Roman structures
Pre-Hellenistic drowned island
Early Roman coastline
Modern coastline
Ancient jetties (Flaux et al., 2017)
Potential archaeological areas related to Portus Mareoticus (Flaux et al., 2017)

Figure 18

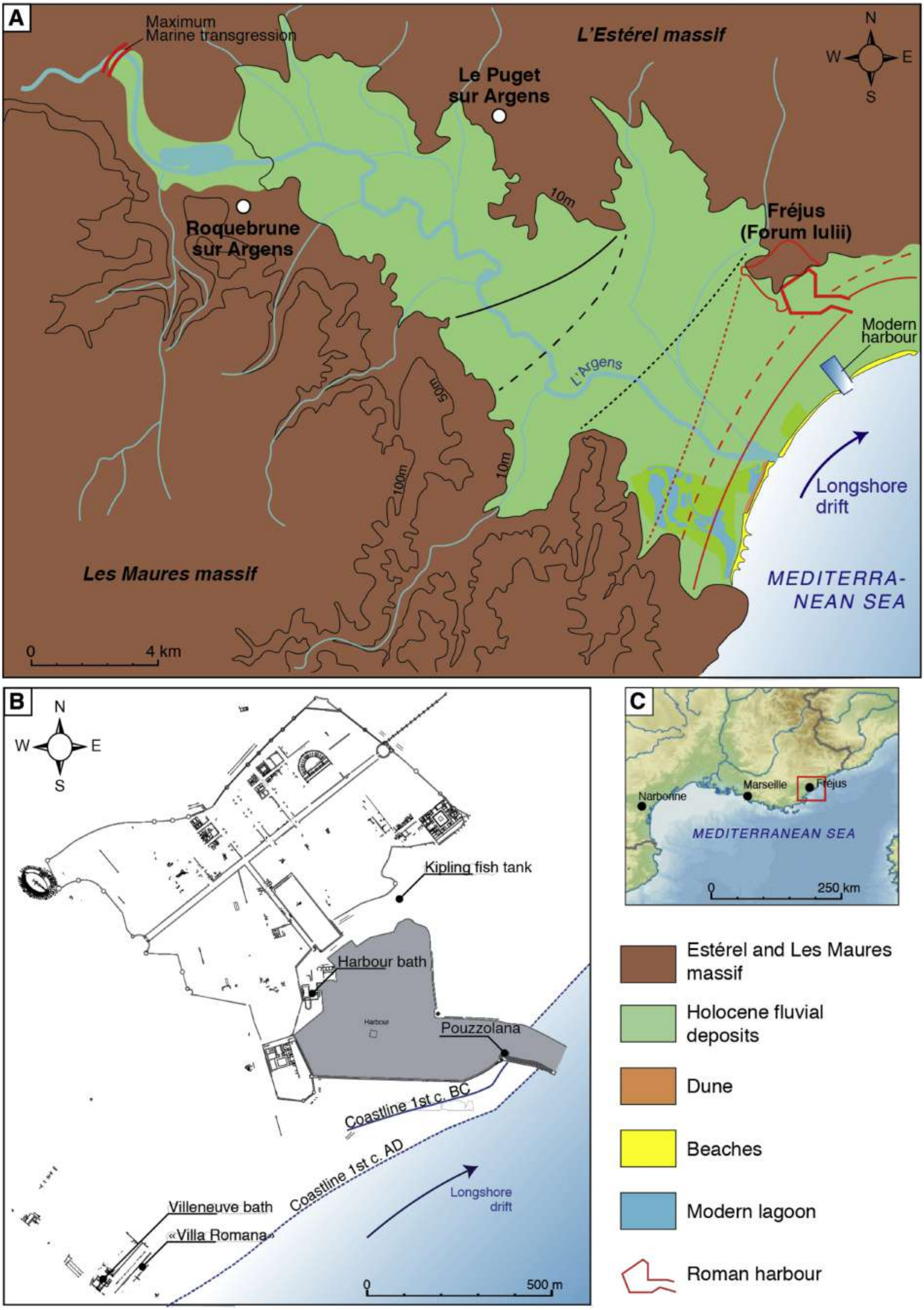

A
Maximum
Marine transgression
L'Estérel massif
N
W
E
S
Le Puget
sur Argens
Roquebrune
sur Argens
10m
Fréjus
(Forum Iulii)
Modern
harbour
L'Argens
50m
100m
10m
Longshore
drift
Les Maures massif
MEDITERRA-
NEAN SEA
0
4 km
B
N
W
E
S
Kipling fish tank
Harbour bath
Harbour
Pouzzolana
Coastline 1st c. BC
Coastline 1st c. AD
Longshore
drift
Villeneuve bath
«Villa Romana»
0
500 m
C
Narbonne
Marseille
Fréjus
MEDITERRANEAN SEA
0
250 km
Estérel and Les Maures
massif
Holocene fluvial
deposits
Dune
Beaches
Modern lagoon
Roman harbour

Figure 19

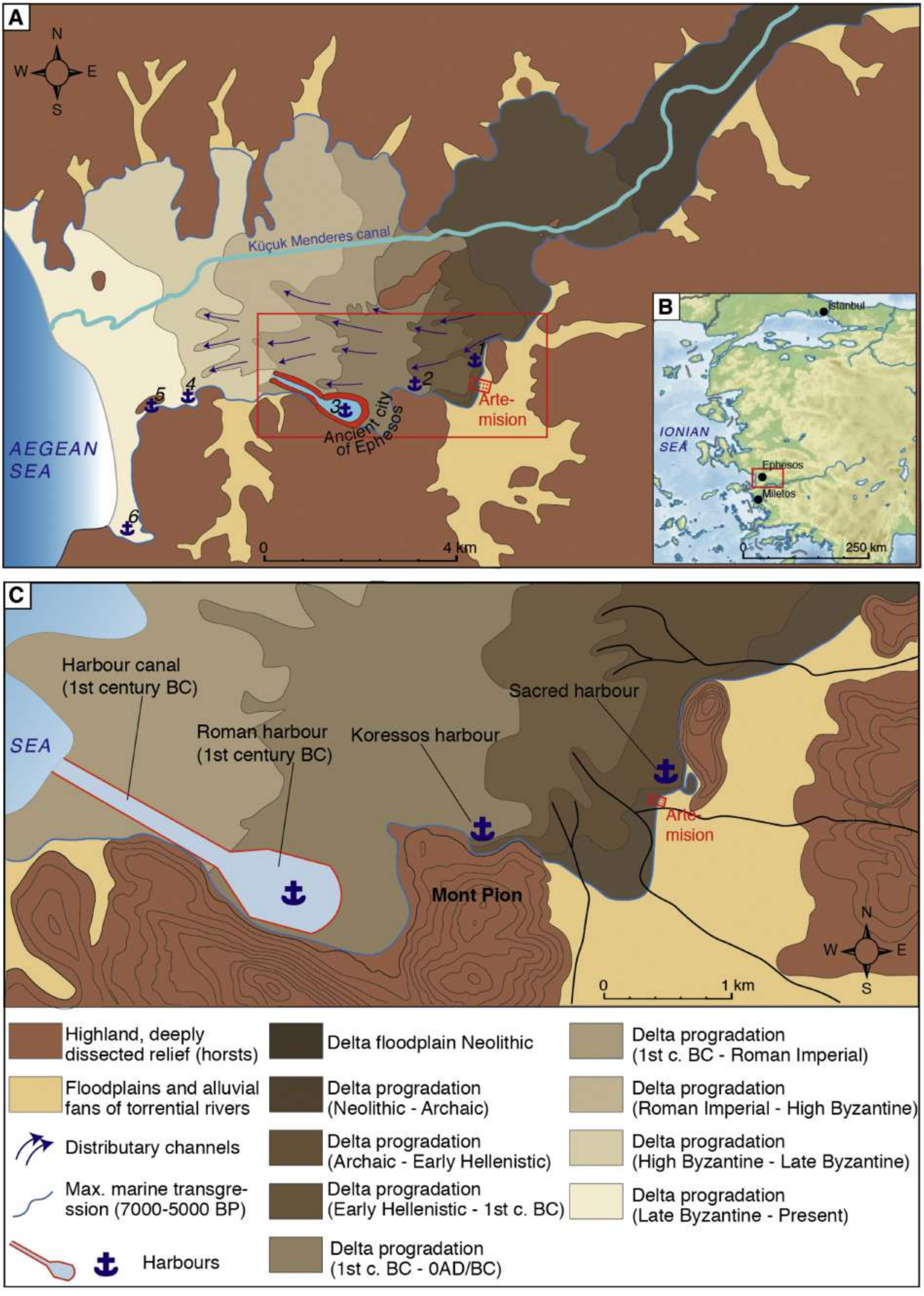

A
N
W
E
S
Küçuk Menderes canal
AEGEAN SEA
Ancient city of Ephesos
Arte-mision
1
2
3
4
5
6
0
4 km
B
Istanbul
IONIAN SEA
Ephesos
Miletos
0
250 km
C
SEA
Harbour canal (1st century BC)
Roman harbour (1st century BC)
Koressos harbour
Sacred harbour
Arte-mision
Mont Pion
0
1 km
Highland, deeply dissected relief (horsts)
Floodplains and alluvial fans of torrential rivers
Distributary channels
Max. marine transgre-ssion (7000-5000 BP)
Harbours
Delta floodplain Neolithic
Delta progradation (Neolithic - Archaic)
Delta progradation (Archaic - Early Hellenistic)
Delta progradation (Early Hellenistic - 1st c. BC)
Delta progradation (1st c. BC - 0AD/BC)
Delta progradation (1st c. BC - Roman Imperial)
Delta progradation (Roman Imperial - High Byzantine)
Delta progradation (High Byzantine - Late Byzantine)
Delta progradation (Late Byzantine - Present)

Figure 20